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LUNAR AND PLANETARY SCIENCES IN SPACE EXPLORATION

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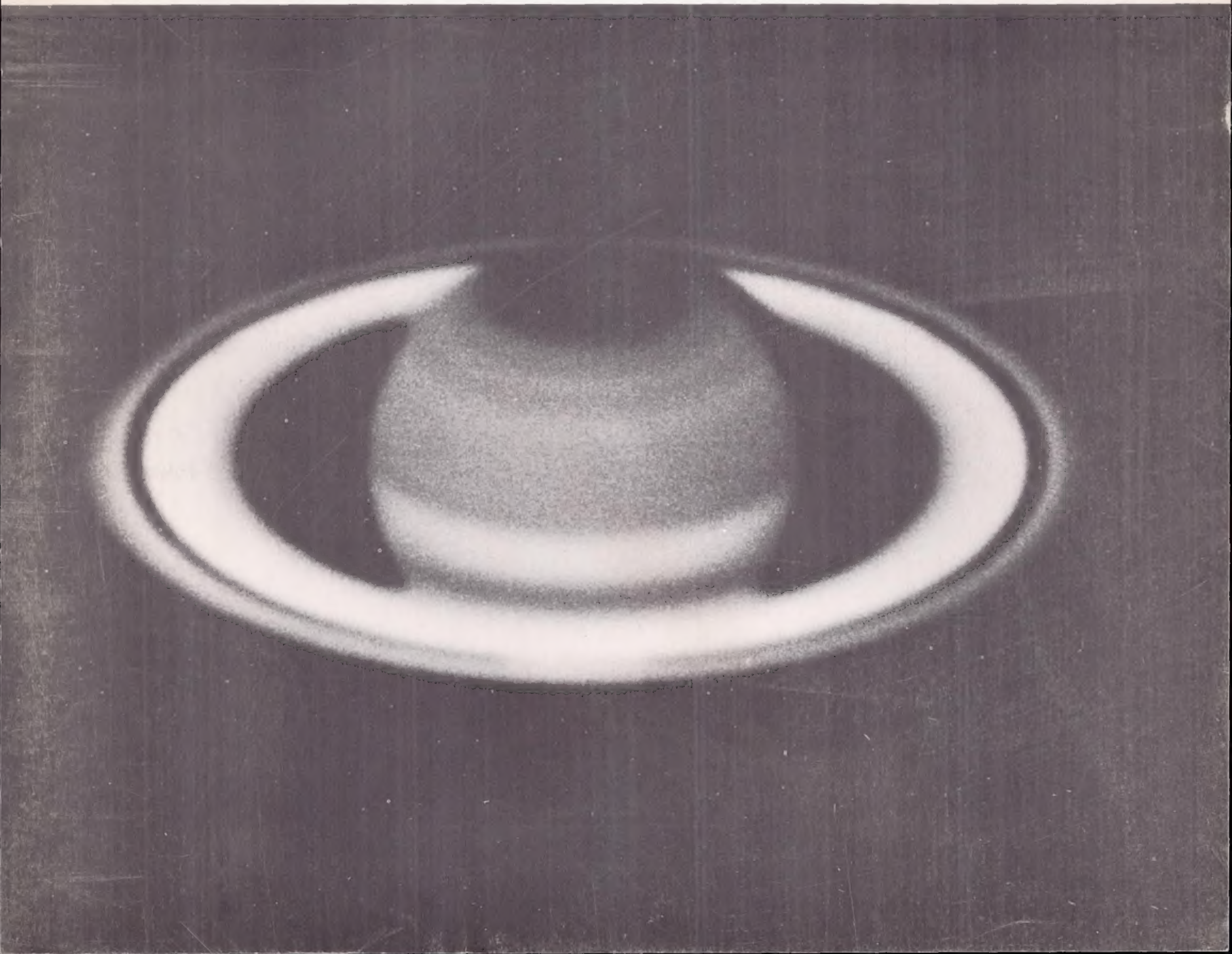

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SESSION H

~~Lunar and Planetary Sciences~~

Chairman, ROBERT B. MEGHREBLIAN

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Lunar and Planetary
Sciences in Space Exploration

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N63-11092

9. Radar Astronomy

By Walter K. Victor

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SUMMARY

Five questions of general interest are answered briefly: (1) What is radar astronomy? (2) How does radar astronomy differ from radio astronomy? (3) What constitutes a radar astronomy observatory? (4) What can be learned by pursuing scientific and engineering research in the field of radar astronomy? (5) Should radar astronomy receive serious academic support?

INTRODUCTION

At 2000 hours GMT on November 12, 1962, Venus will approach within 24.9 million miles of Earth, thereby providing radar astronomers with another opportunity of exploring our nearest planetary neighbor. The last inferior conjunction of the Earth and Venus occurred on April 10, 1961, very nearly 19 months ago. During the last opportunity, five different organizations in three different countries gathered and published data (Ref. 1–5) relative to a radar-derived value for the astronomical unit which were in very close agreement. It is hoped that these and other organizations will be able to participate in this year's experiments.

In general, the objectives for such experiments are to improve the accuracy of the astronomical unit, to investigate further the nature of the surface of Venus as determined by the reflectivity of its surface, to determine whether Venus spins on its axis, to determine its rotational speed, and to determine the orientation of the planet's spin axis. However, before elaborating on the subject of planetary radar astronomy, let us define radar astronomy in general.

WHAT IS RADAR ASTRONOMY?

Webster's dictionary defines radar as "a radio detecting device that emits and focuses a powerful scanning beam of ultra-high-frequency waves and establishes through reception and timing of reflected waves the distance, altitude, and direction of motion of any object i nthe path of the beam unhindered by darkness, storm, cloud or fog." It also defines astronomy as "the science which treats of the celestial bodies, their magnitudes, motions, constitution, etc." Combining these two definitions, then, radar astronomy would be a science that treats of the celestial bodies and investigates their magnitudes, motions, constitutions, etc., by radar.

Another possible definition of radar astronomy is "a science that investigates celestial bodies in our solar system by comparing the instantaneous form of a reflected radio wave —that is, its amplitude, frequency, phase, and polarization—with that of the transmitted radio wave." Any differences, except for the normal reduction in average amplitude due to distance, are commonly identified as signal distortion. To the communications engineer, distortion of his transmitted waveform by random

multipath phenomena or signal fading is a very undesirable occurrence, and he labors diligently to design a radio link which is as nearly free of distortion as possible. A typical radar engineer is primarily interested in measuring true time delay of his transmitted waveform, and any other form of distortion is objectionable because it reduces the accuracy of his range measurement. The radar astronomer, on the other hand, is delighted to find his transmitted waveform distorted because it is the distortion components of the waveform which contain the desired information about the celestial bodies of interest.

To broaden the scope of his field of investigation the radar astronomer has included as extraterrestrial targets anything that reflects a radio signal. Therefore, we find that there are "hard" targets, such as the Moon and the planets, and "soft" targets, such as ionospheres, atmospheres, solar corona, meteor trails, comets, etc. For the sake of completeness our definition of radar astronomy should include both "hard" and "soft" targets.

HOW DOES RADAR ASTRONOMY DIFFER FROM RADIO ASTRONOMY?

The most important distinguishing difference between radar astronomy and radio astronomy is that radar astronomy signals initiate from an Earth-based man-made transmitter, and their basic characteristics such as waveform, bandwidth, and polarization are selected and controlled by the experimenter; whereas radio astronomy signals are generated extraterrestrially by some natural phenomena in the universe, and their characteristics are usually like those of thermal noise.

If we examine the types of measurements made by radio and radar astronomers, we find that radio astronomers measure such things as the size, position, brightness, radio spectrum, distribution, and polarization of radio sources in the sky and on the Sun; whereas radar astronomers, on the other hand, make measurements of range, velocity, radar cross-section, bandwidth and shape of the radio spectrum, echo power as a function of delay of echo spectrum as a function of delay. The radio astronomers, of course, have many more signal sources outside the solar system than inside; whereas radar astronomers will probably always have to restrict their activities to targets within the solar system.

However, to the outside observer a radar astronomy facility may look very much like a radio astronomy facility. This is due to the fact that they both employ large, steerable parabolic-reflector antennas. For targets near the Earth these antennas may range from a few feet in diameter to 20 or 30 ft; whereas for extreme-range targets it is advantageous to use antennas with diameters of 60 to several hundred ft. Radio and radar astronomy receivers are a lot alike in that they must possess very stable gain, bandpass, and noise temperature characteristics. However, they may differ quite drastically in predetection bandwidth if the radar astronomer chooses to transmit a narrowband signal.

WHAT CONSTITUTES A RADAR ASTRONOMY OBSERVATORY?

One way of answering this question is to describe the Goldstone observatory, which is located in the Mojave desert about 120 miles northeast of Los Angeles. The Goldstone Tracking Station is part of the Deep Space Instrumentation Facility (DSIF), which is managed and operated by the Jet Propulsion Laboratory for the National Aeronautics and Space Administration. At the time of the last Earth-Venus conjunction, in April 1961, its two 85-ft-diameter antennas were not being utilized to track deepspace probes, and they were made available to a small group of JPL research engineers and scientists to perform a radar experiment using Vensus as a target. As mentioned earlier, the JPL Venus radar experiment was one of five performed during the inferior conjunction of 1961. Other radar experiments were performed by the Lincoln Laboratory of MIT, the University of Manchester Jodrell Bank Station in England, RCA, with a ballistic missile early-warning radar, and the Soviet Academy of Sciences. Since JPL was the only one of the five organizations to utilize two antennas, the observatory to be described will differ in this respect from the others. However, during the November 1962

Earth-Venus conjunction, JPL is using a single antenna because two large antennas could not be made available by the DSIF during this time period due to the need to track Mariner 2 on its way to Venus.

Figure 9–1 is a map showing the location of the Goldstone Tracking Station with respect to Los Angeles and JPL. It is 45 minutes from Los Angeles by plane, or 3½ hours by automobile. This site was selected because it is remote from civilization, the closest town, Barstow, being about 40 miles away.

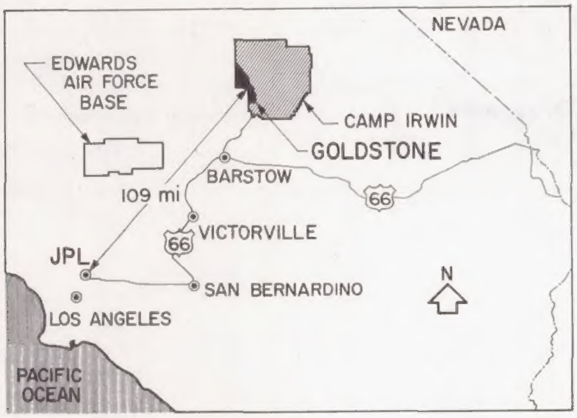

FIGURE 9–1.—JPL-Goldstone map.

Figure 9–2 is an aerial view showing the barren nature of the desert site and the hilly terrain, which has been utilized effectively to provide additional isolation from man-made rf interference. The first equipment was installed in the latter half of 1958 in a bowl-shaped area and was used initially for receiving only; hence, it was called the receiving site. Later, when it was decided that JPL should participate in Project Echo, a transmitting antenna was located seven miles from the receiving site and isolated from it by hills to reduce rf coupling. The lake in the foreground of figure 9–2 is Goldstone Lake, a dry lake which has been converted to an air strip.

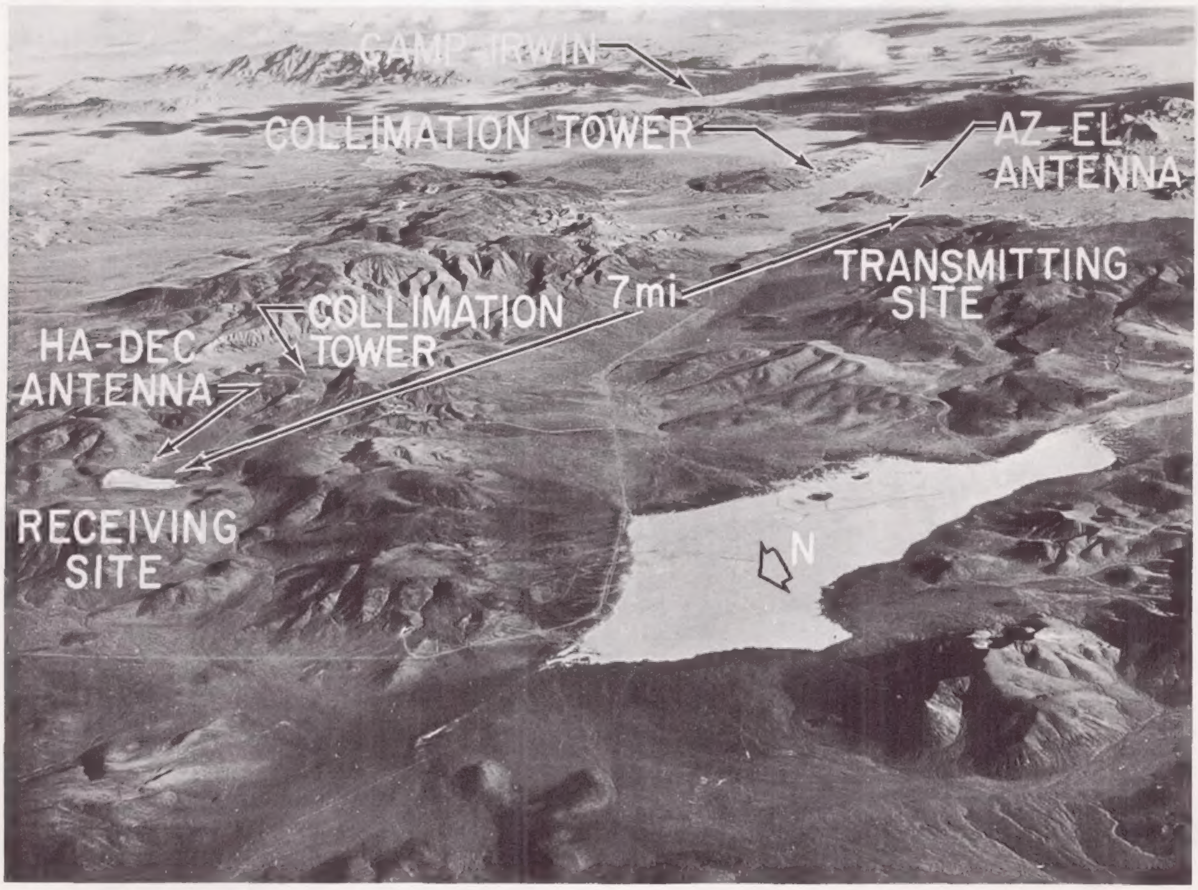

FIGURE 9–2.—Goldstone tracking station.

Figure 9–3 is a photograph of the 85-ft hour angle-declination (HA-Dec) antenna located at the receiving site. The antenna was initially designed for radio astronomy use, and several of them are being utilized for this purpose by various organizations at the present time. The HA-Dec mount was selected because the principal use of the antenna by the DSIF is for tracking deep-space probes which move very slowly in celestial coordinates.

FIGURE 9–3.—85-ft. diameter Goldstone hour angle-declination (HA-Dec) antenna.

Figure 9–4 is a photograph of the 85-ft Goldstone transmitting antenna which was installed during the latter half of 1959 and used for Project Echo in mid-1960. The azimuth-elevation mounting arrangement was chosen to provide additional flexibility for experimental satellite communications and to serve as a prototype for a still larger steerable antenna presently under study for deep-space communications work. A microwave relay connects the two sites, and either antenna may be slaved to the other by means of a digital coordinate converter and digital servo drive system. Both antennas are equipped with digital readouts. (Table 9–1)

FIGURE 9–4.—85-ft.-diameter Goldstone azimuth-elevation (Az-El) antenna.

TABLE 9–I.—*Venus Radar System Parameters*

Unmodulated transmitter power (12.6 kw)	+71	dbm
Transmitter antenna gain	+53. 8	db
Transmitter line loss	−0. 3	db
$\frac{\sigma}{4\pi R^2}$ at 31 million miles	−84	db
Power intercepted by Venus	+40. 5	dbm
$\left(\frac{\lambda}{4\pi R}\right)^2$ at 31 million miles	−255	db
Apparent reflection and propagation loss	−9	db
Receiving antenna gain	+53. 5	db
Typical received signal level	−170	dbm
Receiver threshold (T=60°K, BW=1 cps).	−181	dbm
Typical signal-to-noise ratio	+11	db

Table 9–I shows the basic parameters of the Goldstone radar for detecting a Venus radar echo. With an unmodulated transmitter power of 12.6 kw or +71 dbm, a transmitter antenna gain of 53.8 db, and a transmitter line loss of 0.3 db, the power intercepted by Venus at a distance of 31 million miles is approximately 10 watts or +40.5 dbm. If the apparent reflection and anomalous propagation loss is 9 db and the receiving antenna gain is 53.5 db, then the received signal level is approximately 10^{-20} watts or −170 dbm. If the receiver has a threshold of −181 dbm, based on a noise temperature of 60°K and an effective bandwidth of 1 cps, a typical signal-to-noise ratio will be approximately 11 db. For a change in range from 26 million to 37 million miles, obtainable over a period of about two months, the signal-to-noise ratio will vary from 14 to 8 db, respectively. The effective bandwidth of 1 cps was obtained with a predetection bandwidth of 25 cps and a postdetection integration time of 68 seconds. The temperature of 60°K was obtained using a maser followed by a parametric amplifier.

Several different transmitted waveforms were used during the experiment to gather different types of information. Figure 9–5 is a block diagram of the configuration used for measuring signal level. The receiver operates

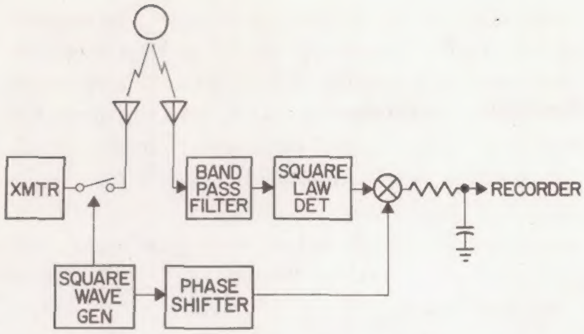

FIGURE 9-5.—Radiometer block diagram.

very much like a switched radiometer except for the fact that the transmitter (instead of the receiver) is switched on and off to permit the receiver to difference signal-plus-noise with noise alone.

WHAT CAN BE LEARNED BY PURSUING SCIENTIFIC AND ENGINEERING RESEARCH IN THE FIELD OF RADAR ASTRONOMY?

Before attempting to answer this question, let us examine what has been accomplished to date, and in this way arrive at a plausible prediction as to what may be accomplished in the future by radar astronomy. Figure 9-6 is a graph showing the astronomical unit in millions of kilometers as a function of time in years beginning with the year 1900 (Ref. 6). All of the determinations through 1953 were determined by classical astronomers using optical techniques. Based on these results the International Astronomical Union decided that the best figure for the astronomical unit should be 149.5 million km, shown by the heavy black

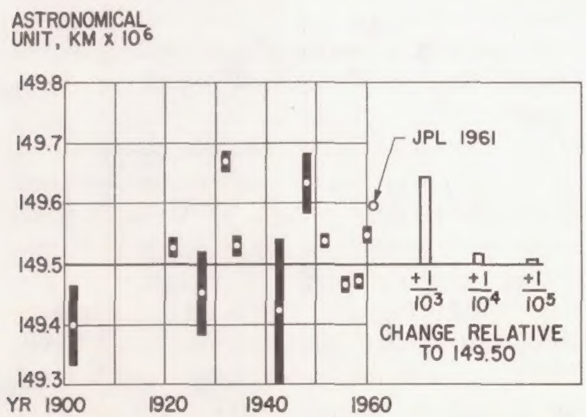

FIGURE 9-6.—Determination of the astronomical unit.

line. Beginning in 1958 the new determinations were obtained using radar methods. In spite of the small probability of error associated with the radar determinations in 1958 and 1959, it is generally agreed based on the 1961 data that the new value for the astronomical units as determined by radar means is very close to 149.6 million km. The Lincoln Laboratory of MIT and Jodrell Bank, which performed the earlier experiments in 1958 and 1959, respectively, have now decided, based on their 1961 results, that the earlier determinations were in error and should be disregarded (Ref. 2, 3). As may be seen from the graph, the change from 149.5 to 149.6 million km represents a change of ⅔ of a part in 10^3, or 0.067%. It may also be observed that only one previous determination of the IAU agrees with the radar measurement. This previous determination was made by Brower in 1948, based on perturbations of the orbit of the Moon (Ref. 6).

If we examine the region around 149.6 km in more detail and compare the measurements the results of their Venus radar measurements made by the five organizations who reported on we find, in Figure 9-7, that there is very close

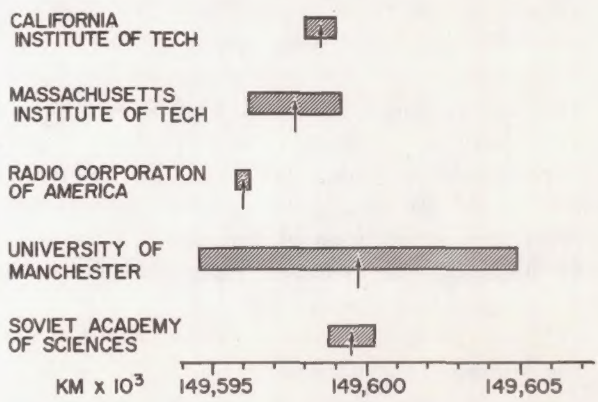

FIGURE 9-7.—Radar measurement of astronomical unit in April 1961.

agreement indeed. The average of these values falls very close to 149,598,300 km for the value of the astronomical unit as determined by radar measurements made during the April 1961 inferior conjunction.

Although we usually think of a radar as measuring only angles, doppler, and range, the instrument is much more versatile. As mentioned earlier, if we chose the correct waveform

to transmit and examine carefully the differences between the transmitted and received waveforms, a great deal can be learned about the nature of the target. For example, when a line spectrum was transmitted to Venus on April 21, 1961, the signal returned doppler-broadened with the shape shown in figure 9–8. The waveform was apparently modulated by

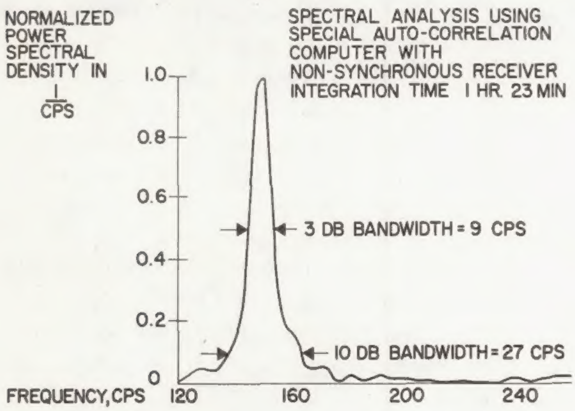

FIGURE 9–8.—Venus-reflected signal, April 21, 1961.

the planet in both amplitude and phase, resulting in a spectrum whose 3-db bandwidth was 9 cps and whose 10-db bandwidth was 27 cps after an integration time of 1 hour and 23 minutes. Several of these spectrograms were recorded during a period of three to four weeks and were compared and analyzed. Small variations in bandwidth and spectral shape were noted, but much more data are required before definite statements can be made about rotational speed, axis of rotation, or nonuniformity of radar reflection characteristics as a function of Venus longitude.

From the measurements of the strength of the reflected signal (see Table 9–11), it was determined that Venus is a much better radio reflector than the Moon at kilomegacycle frequencies, having an apparent radar cross-section of about 11% of its geometrical cross-section as opposed to about 2½% for the Moon. The radar cross-section is labeled "apparent" since it is calculated assuming no additional loss over the free-space loss normally expected on the trip to and from Venus.

The results of a polarization reversal test indicated that Venus has a surface roughness comparable to that of the Moon when the roughness is of the order of the wavelength of the radio frequency signal. This test was performed by reversing the polarization sense of one of the antennas and noting that the signal level decreased by approximately 12 db. In similar experiments on the Moon, mismatched polarization produced a signal approximately 11 db below that produced with matched polarization, very nearly the same as that for Venus.

TABLE 9–II.—Scientific Results of Venus Experiment

1. Astronomical unit.	149,598,500 ±500 km.	Time of flight measurement.
2. Venus surface.	Apparent radar cross-section 11% ±2% of geometric cross-section.	Signal strength measurement.
	Small-scale roughness similar to Moon.	Circular-wave depolarization measurements and rotatable linear polarization measurements.
3. Venus rotation rate and axis orientation.	200–400 Earth days suggests trapped rotation of 225 days.	Spectral measurements.

For the future it should be possible to refine the astronomical unit using radar methods at least to the same accuracy as we know the velocity of radio propagation in interplanetary space. When sufficient radar data become available to define the Earth-Venus distance over a complete cycle, it should be possible to combine radar and optical data in such a way as to derive new and more accurate heliocentric ephemerides of Venus and the Earth-Moon system.

Careful measurement of echo spectra will definitely permit us to refine our present estimate of the rotation rate of Venus and the orientation of its axis. For example, Figure 9–9 is a graph showing the calculated limb-to-limb bandwidth of a Venus echo spectrum as a function of time for the period around Earth-Venus conjunction in November 1962. For a synchronously rotating Venus, which always presents the same face to the Sun, the band-

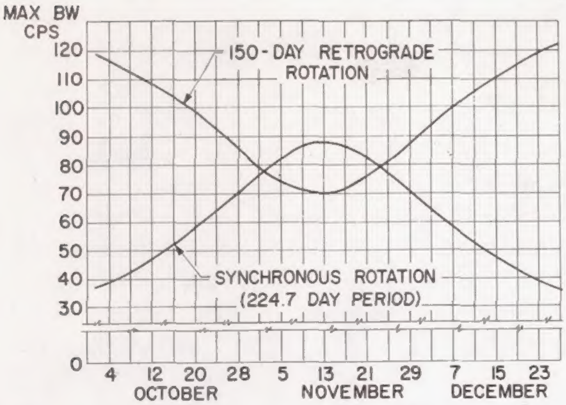

FIGURE 9-9.—Maximum bandwidth spread vs time.

width would *increase* before conjunction by more than a factor of 2 in 6 weeks and decrease after conjunction by the same amount. On the other hand, if Venus has a retrograde rotation with a 150-day period (see also figure 9-1), the bandwidth would *decrease* significantly before conjunction and increase after conjunction. Temporal variations in spectral characteristics and in apparent radar cross-section may eventually tell us whether the surface is uniform or whether it has oceans or land masses like the Earth.

With increased power we should be able to establish radar contact with Mercury, Mars, and even the planet Jupiter. Figure 9-10 shows the range from the Earth to Venus in millions of kilometers as a function of time in years. On April 1961 Venus approached within 26 million miles of the Earth. Inferior conjunction of Venus and the Earth will occur again in November 1962 and continue to occur every 19.2 months thereafter. Using the information already gained about the characteristics of the radio signal reflected from Venus, it is now possible to track Venus for six months out of every 19-month period without making any further improvement in the performance of a Goldstone-type radar. However, by increasing the transmitter power to 100 kilowatts and reducing the receiver temperature to about half of its present value, both modifications well within the present state of the electronic art, it is possible to increase the range by a factor of 2 as indicated by the line marked +12 db on figure 9-10. With these changes it would be possible to track Venus steadily for about twelve months, losing it only for a short period near superior conjunction.

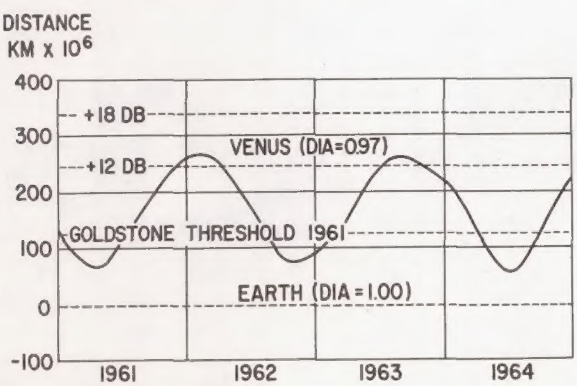

FIGURE 9-10.—Radar detectability of Venus with Goldstone-type radar.

Figure 9-11 shows the range from Earth to Mercury as a function of time. Mercury approaches within 60 million miles of the Earth approximately every four months. Assuming Mercury has the same reflectivity as Venus, and accounting only for its smaller diameter, about one-third that of the Earth, Mercury is not quite detectable with the present Goldstone radar. However, with the indicated 12-db improvement it is seen that Mercury too could be observed over a period of about two months. If it were possible to improve the present system by about 18 db, both Mercury and Venus could be observed continuously whenever they were above the local horizon.

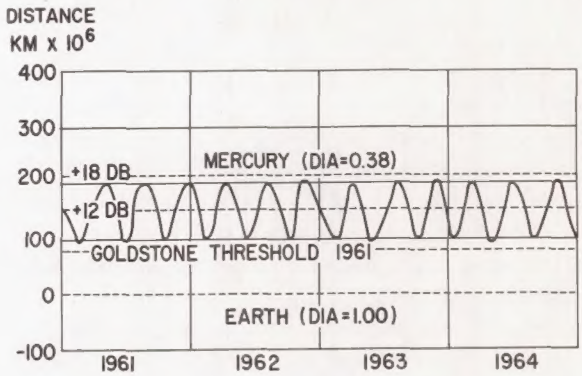

FIGURE 9-11.—Radar detectability of Mercury with Goldstone-type radar.

Figure 9-12 shows a similar chart for the planet Jupiter. Jupiter approaches roughly within 400 million miles of the Earth about once each 13 months. However, because of

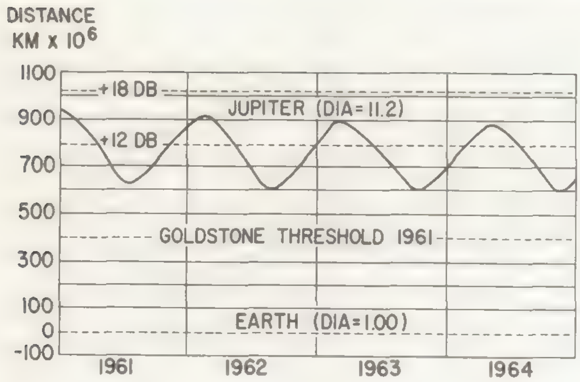

FIGURE 9–12.—Radar detectability of Jupiter with Goldstone-type radar.

its tremendous size, about 11 times the diameter of the Earth, and with 132.5 times as much reflecting surface as Venus, it may also be detectable by a modified Goldstone radar if the reflectivity is similar to that of Venus and if a major portion of the return echo is contained in a relatively narrow bandwidth.

Figure 9–13 shows the conjunctions of Earth and Mars. Mars approaches within about 60 million miles of the Earth at intervals of just under 26 months. However, because of its small size, about half the diameter of the Earth, and the variation in Earth-to-Mars distance by a factor of 7 between the closest opposition and the farthest conjunction, it would only be detectable for a portion of its orbit even with an improved system and a highly specular planet.

SHOULD RADAR ASTRONOMY RECEIVE SERIOUS ACADEMIC SUPPORT?

This same question was asked about radio astronomy during the decade following the discovery of extraterrestrial radio waves by Karl G. Jansky in December 1931. For radio astronomy, at least, the question has been answered definitely in the affirmative, and increasing numbers of universities and technical institutes are sponsoring research and providing academic courses in radio astronomy. In the case of radar astronomy, however, in spite of the fact that lunar radar echoes were received for the first time in January 1946, very few universities have become interested in this subject even after a period of more than 16 years, and very few, if any, facilities have been built exclusively for lunar radar research.

However, two things have happened in the last few years that could change this attitude toward radar astronomy. One is the national program of manned exploration of the Moon, which has aroused new interest in the Moon as an object for further observation, study, and analysis. The suggestion here, of course, is that a great deal of new information about the Moon can be obtained from active university-type research programs in lunar radio and radar astronomy. The second thing that has happened which could affect university participation in radar astronomy is the newly demonstrated feasibility of exploring the planets—Venus, Mars, Mercury, and Jupiter—by radar.

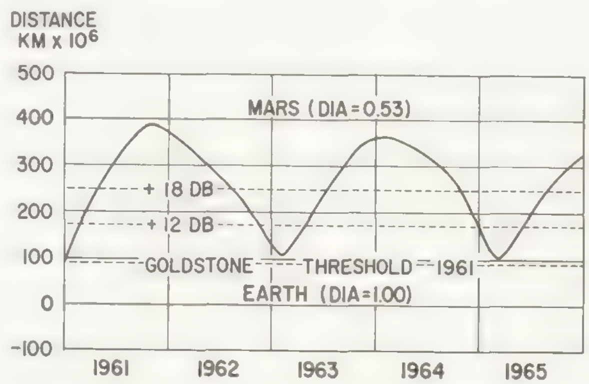

FIGURE 9–13.—Radar detectability of Mars with Goldstone-type radar.

Table 9–III presents a list of universities which have large, steerable, parabolic-reflector antennas, at least 60 ft in diameter, which are or will be assigned to radio astronomy depart-

TABLE 9–III.—Universities with Large Reflector Antennas for Radio Astronomy

School	*Reflector diameter, ft*	*Location*
Carnegie Institute	60	Rockville, Maryland.
Harvard College	60	Harvard, Massachusetts
	85	Fort Davis, Texas.
Stanford University	60	Palo Alto, California.
	150	
University of Alaska.	61	College, Alaska.
Massachusetts Inst. of Technology.	84 120	Westford, Mass. (under construction)
Univ. of California at Berkeley.	85	Hat Creek, California.
Univ. of Michigan	85	Durban, Michigan.
California Institute of Technology.	90 (2)	Owens Valley, California.

ments for student training and research. At the present time, almost all of these antennas are used for radio astronomy. If a high-power transmitter were added to the facility (at a cost that is roughly comparable to the cost of the antenna), the antennas could be used for either radio or radar astronomy research.

I feel quite strongly that radar astronomy should and will receive serious academic support, because it possesses many areas for fruitful research in both engineering and science and because it is engendering many new and fundamental principles in information and detection theory which place it on a solid, technical foundation.

ACKNOWLEDGMENT

The principal source of information concerning the 1961 JPL Venus radar experiment is Ref. 7, which was written by scientists and engineers directly responsible for the success of this experiment. The author gratefully acknowledges their work and the inspiring project leadership of his colleague, R. Stevens. The author also wishes to acknowledge the support provided throughout the planetary radar project by Dr. E. Rechtin, the DSIF Program Director, and to thank him for his helpful comments and criticisms in reviewing this paper.

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N63-11098

15. The Scientific Exploration of Deep Space

By Manfred Eimer

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INTRODUCTION

One of the goals of the exploration of the solar system with manned and unmanned probes is to obtain an understanding of the origin and properties of the phyical bodies which make up this system and of the origin, distribution, and properties of life within it. Consideration of deep space excludes the Earth and its near vicinity as a specific target for study. It must be evident, however, that one of the major motivations for extraterrestrial exploration is curiosity about ourselves, our origin, and our environment.

The exploration of the solar system by means of probes is not the only method of obtaining such data, but it is clearly the most hazardous and expensive, and in many instances, the most difficult. It is essential, therefore, that the present and planned expansion of effort using unmanned and manned spacecraft be led by or at least paralleled by an expansion of activity using conventional and unconventional Earth-bound methods. The pursuit of data by these methods is worthy of the best possible effort so that space probes not be used for measurement when other means are possible, and maximum results are obtained when their use is necessary. Similarly, the utilization of unmanned probes should be maximized in order to minimize the burden on the use of manned spacecraft. The question should not be, what can deep space probes do, but rather, what can Earth-bound methods *not* do and, analogously, the question should not be, what experiments can be performed with manned spacecraft, but rather, what experiments *cannot* be done sufficiently well without man's presence at or near the source of data.

For the present purposes, the targets of exploration can be grouped into four categories. First, the Sun and its atmosphere to the outer reaches of the planetary system near and far from the ecliptic plane; second, the planets Venus and Mars; third, the Moon; and fourth, the distant planets and their moons, the asteroids, and the comets. With respect to the first three of these categories, it is possible to discuss potential steps of exploration, their interrelationship, and their relevance to the crucial scientific questions, with a sense of practicality and immediacy not possible with respect to most of the targets in the fourth category. With respect to that group, the question is not how and why should the exploration of each target be accomplished but which of these targets is it possible to explore in the near future. While it may well be that the most immediate and possibly one of the most rewarding first targets will be the comet Encke, even for that venture it may be premature to undertake detailed scientific planning.

With the exception of the rudimentary photographs obtained by the Russian probe Lunik III, essentially all observations of the Sun, of the planets, Venus and Mars, and of the Moon were made from the Earth and near Earth in the electromagnetic spectrum. These observations and measurements have been passive with respect to all these bodies and additionally have been active in the microwave region with respect to the Moon and Venus and active in a preliminary way in the near-infrared with respect to the Moon. The analysis of the shreds of data obtained in this manner to date have permitted scientists capable of bridging the several scientific disciplines involved to weave a fairly substantial fabric of understanding of some aspects of the properties of these bodies. Isolated and misinterpreted data have in past decades invited fairly widespread speculation, often by untrained amateurs, which has sometimes tended to emphasize, particularly with respect to the Moon and planets, what the surfaces could be like rather than what they should be expected to be. This excessive speculation, which has tended to obscure the distinction between science and science fiction, may have in part, been responsible in this country for the relatively limited participation of scientists in studies of the Moon and planets. The shortage of observing time made available for this purpose by observatories having equipment of adequate caliber may be a symptom of this problem.

It is not the purpose of the present paper to attempt to review the status of solar physics or of the lunar and planetary sciences but rather to discuss the contribution that the exploration of deep space by manned and unmanned probes can make to three crucial scientific questions. These questions are:

1. Steller evolution and the synthesis of elements.
2. The formation of the planetary system.
3. The origin of life.

CRUCIAL QUESTIONS

Stellar Evolution and the Synthesis of Elements

There are three disciplines which at the present time provide the bulk of pertinent observational data. These are: astrophysics, which in the present context provides data on the relationship between age and type of star and certain general stellar processes and elemental abundances; solar physics, which provides data on present detailed properties, processes and elemental abundance of the Sun; and geo- and cosmochemistry, which provide data on the relative elemental and isotopic abundances of the Earth's crustal material and of the relatively meager bits of meteoritic material available for that purpose.

It is unlikely that flights of deep-space probes will in this decade contribute astrophysical data. It is also unlikely that spectroscopic measurements of the Sun can be made more advantageously from deep space than from near Earth. Nevertheless, the Sun is the only star on which certain observations can be made from deep space probes that cannot be made from the Earth or from regions near Earth. It can be argued that a best possible understanding of present solar properties and processes may contribute to the extremely complex general problem of stellar evolution.

Observations of the Sun which can be made only from deep space probes include:

1. Measurements of mass flux as a function of solar latitude.
2. Measurements relating to the structure and properties of solar plasma.
3. Measurements of the solar and, possibly, the galactic magnetic fields.
4. Measurements of the fluxes of relatively short-life-time particles.
5. Direct measurement of processes in the outer fringes of the corona.
6. Separation of spacial and temporal phenomena by simultaneous measurement from differing heliocentric coordinates or by scanning the ecliptic plane from a vantage point far from that plane.

While it is beyond the scope of the present paper to relate in detail how results from experiments of the type listed contribute to the general problem, it is worth noting that at least four types of missions are required to carry out the observations.

1. Solar probes to within ten solar radii from the Sun's center, the closest distance for which

a space-probe design can be extrapolated from present technology.

2. Simultaneous measurements from at least two probes approximately one astronomical unit from the Sun and moving far from the Earth.

3. Probes capable of reaching beyond five astronomical units.

4. Out-of-the-ecliptic probes to at least 25° of solar latitude.

Instruments carried on missions of these types should have a broad capability for measuring the properties of fields, particles, and radiation.

By astronomical methods, the average densities of the Moon and Mars have been determined and for Venus and some of the other planets, they have been estimated. Direct observational data relating to the composition of stars, of the Sun, and of the atmospheres of several of the planets have been obtained. Only in rare instances have isotopes been differentiated by these methods (Ref. 1). For the Earth's crust and the available meteoritic material, relative elemental and isotopic abundances have been determined. Studies of the synthesis of elements rely on these conventional data and theoretical considerations.

Deep-space probes are a potential course of cosmochemical data of immeasurable significance. Spacecraft that fly by or orbit Mars and Venus carrying microwave, infrared, and ultraviolet spectrometers can obtain data which are capable of substantially increasing our understanding of the composition and structure of the planetary atmospheres. Gamma-ray spectroscopy from impacting or orbiting spacecraft and possibly X-ray and neutron spectroscopy from orbiters can provide data on lunar surface composition.

Complete and precise elemental analyses can be accomplished only, however, by direct processing of surface and subsurface material *in situ* or after bringing the samples to Earth. It appears unlikely that isotope ratios will, in general, be determined by *in situ* analysis in the near future but will require the carrying of samples to Earth. A wide variety of analysis instruments capable of automatic operation on the lunar surface have been studied, and some are in advanced stages of development. It is with the landing of these instruments and the subsequent return of lunar surface and subsurface material, which will provide the first such data on extraterrestrial material of certain source, that vital new data on the distribution of elements and isotopes will be obtained. These data and similar data from the near planets must certainly contain clues for the solution of certain puzzling aspects of the problem of the synthesis of elements.

The Formation of the Planetary System

The present data on which theories of the formation of the planetary system are based include the physical evidence of the position, motion, masses, and densities of the planets and their satellites; the nuclear evidence from the Sun, the planets with atmospheres, the Earth, and meteorites; and the mineralogical data from the Earth's crust and from meteorites (Ref. 2). These data have given rise to several modern theories which attempt to explain the formation of the planetary system, none of which can be considered completely satisfactory. The limited data obtainable from Earth are sufficient to provide constraints for an unambiguous theory of planetary system evolution.

In the present context, it can be said that the mass, dimensions, motion, and major constituents of the atmosphere of Mars are reasonably well known. However, the magnetic field strength, mass distribution, surface chemistry and structure, and the abundance of most rare constituents in the atmosphere cannot be determined by Earth- or near-Earth-based instruments. All can either be determined completely, or at least in a preliminary way, from space probes which it is possible to launch in this decade.

Venus is even less understood. Only carbon dioxide has been measured directly in the atmosphere, and the abundance of the dominant constituent, nitrogen, is inferred. The mass and dimensions can be estimated, but its rotational motion has not been conclusively determined. While its surface is almost certainly hot, the mechanism for producing this relatively high temperature is not yet understood. Its surface chemistry is almost completely unknown

except for what is inferred from the high surface temperature, somewhat high carbon dioxide concentration, and probably low water vapor concentration in the atmosphere. All of these uncertainties or unknowns can be resolved or determined, at least in a preliminary way, from space probes which can be launched in this decade.

During this time, the exploration of Mars and Venus will almost certainly be limited to the use of unmanned probes. The earliest of these, Mariner II, is in transit to Venus at the present time and is expected to arrive at closest approach on December 14, 1962. It is instrumented to make measurements relating to the planetary magnetic field and to the structure and temperature distribution of the atmosphere. It is a member of the simplest category of planetary probes, the flyby. Probes capable of flying by Mars would be able to make measurements relating to the planetary magnetic field and to the atmospheric composition and structure, and in a preliminary way, of obtaining pictures of relatively large-scale surface structures.

Orbiting spacecraft are capable of obtaining in a more complete and sophisticated form data of the type obtainable from flybys. Mass distribution can also be determined from orbiters. The surface structure of Mars is probably determinable from orbiting spacecraft, but Venus may require lifting vehicles for the penetration of the cloud cover.

Detailed measurements of atmospheric structure and composition can be made from capsules designed to penetrate the atmospheres but not necessarily to survive the surface landing. However, the measurements most important for understanding planetary evolution can only be made from soft-landed spacecraft. The measurements of seismic activity, surface physical properties, elemental composition, and mineralogy which may be directly relatable to the history of the planetary body can only be made in this manner. Sample return vehicles launched from such spacecraft would contain treasures of tremendous scientific value. These samples would permit the obtaining of isotope ratios in addition to the definitive determination of a number of other properties.

It is perhaps a stroke of good fortune that the Moon, our nearest and most accessible celestial neighbor, may prove to contain clues relating to the formation of the solar system which transcend all others in importance. The Earth-Moon system represents the only double planet within the solar system. With respect to the Earth, the Moon is relatively large and of low density. It is these and many other puzzling anomalies, unexplainable at the present time because of the limited data available from Earth-bound techniques, which the unmanned and manned program of lunar exploration has the capability of resolving.

Impacting spacecraft have the capability of obtaining relatively high-resolution pictures of the lunar surface, of measuring radar reflectivity, of carrying a gamma-ray spectrometer (for estimating the K^{40} concentration and detecting certain other isotopes that are naturally radioactive or made radioactive by solar particles), and for depositing instruments such as a simple seismometer on the surface. Orbiting lunar spacecraft can carry out radar mapping, measure radar reflectivity, measure surface and subsurface temperatures with microwave and infrared radiometers and spectrometers, carry out preliminary mineralogical mapping by means of an infrared spectrometer, photograph the surface with a high-resolution monocular and a stereoscopic camera system, view the surface in various polarizations and colors, search for atmospheric hydrogen by looking at the surface in the ultraviolet, and map the distribution of certain isotopes by means of a gamma-ray spectrometer. It may also be possible to employ X-ray and neutron spectroscopy usefully. All of these methods and instruments are capable of gathering data not obtainable by other, more conventional Earth-bound methods.

While orbiting spacecraft examine relatively large areas and can be used to obtain relationships between large-scale features, soft-landed manned and unmanned spacecraft should be used to examine relatively small areas in great detail. The area to be investigated by manned and unmanned spacecraft can be substantially increased by supplying a roving capability, and the detail with which the material can be examined can be greatly enhanced if carefully

selected samples are returned by means of manned or unmanned spacecraft.

On soft-landed spacecraft, emphasis can be expected to be given to a visual or photographic examination of surface texture, to the measurement of physical properties such as bearing-strength, hardness, magnetic permeability, etc., to the examination of grain-to-grain relationship by means of a petrographic microscope, to the study of the mineralogy by means of an X-ray diffractometer, to the determination of the elemental composition by means of one of several instruments under development, to the measurement of surface and internal lunar structure by means of passive and active seismic techniques, and to the determination of the planetary and local magnetic field by several possible techniques. Many or most of these measurements can be directly or indirectly related to the problem of lunar origin and history, and can be expected to provide a particularly rich source of data for understanding the formation of the planetary system.

The Origin of Life

For the present purposes, a living substance can be defined to be one capable of replicating and of evolving into functionally more complex forms. The merit of this definition is that it relies on the single general principle known in theoretical biology, the principle of evolution (Ref. 3). The formation of the first replicating molecule must have been preceded by the development of nutrients sufficiently complex to serve these substances efficiently. The nutrients could either have been formed during one of the phases of condensation of the solar system when the light elements must have been very abundant locally or could have been formed by geochemical processes relatively late in solar system evolution. Recent detailed examination has found a number of very plausible ways in which specific, complex organic molecules can be formed. The question is now not how the probiotic nutrients could have been formed, but which of several methods provided the most important source.

If panspernia is excluded, the first replicating molecule was formed out of this broth of probiotic organic substances. These early self-replicating polymers need not have been nucleic acids. The fact that there is no present evidence on Earth for the existence of these forms does not preclude their having once existed, since they most likely would have been delicacies for the later, more sophisticated substances. It is thus the evolutionary process itself which makes it unlikely that tracing back to the earliest life forms on Earth will be completely successful.

There are, therefore, four major questions which may well be unanswerable from evidence gathered on Earth:

1. Are there fundamental general laws of biology in addition to that of evolution?
2. What was the principal source of probiotic nutrients?
3. What were the first self-replicating polymers?
4. Are the nucleic acids a unique solution to the genetic problem?

There is at present a strong indication that experiments from deep-space probes can provide new data of great significance to the resolution of these questions. The exploration of the Moon and of Mars has special significance in this regard.

Even now there are conjectures that life exists or did exist in the past in regions on the Moon, where the environment locally is sufficiently less hostile than that of the typical surface regions to have permitted the establishment of life. While that possibility must be considered fairly unlikely, the possibility that probiotic nutrients were formed by one of the several methods is distinctly feasible. The presence of organic substances in certain meteorities was established in the 19th century. Modern analyses of the carbonaceous chondrites have shown the existence of a number of complex compounds. Urey has suggested that these meteorites might have come from the Moon. Even if this is not the case, the existence of organics in the parent body of the carbonaceous chondrites is evidence that such substances are found extraterrestrially and raises the plausibility of their presence on the Moon. A gas chromatograph specifically designed to implement the search for and the identification of organics on the Moon is under active development at the present time.

The question of the possibility of life on Mars has been an intriguing one for many decades. It has been known for some time that the environment on the Martian surface is sufficiently mild to make possible the existence of life forms not too dissimilar from certain limited classes on Earth. Some experiments have even purported to show that special forms of Earth-life could survive a simulated Mars environment.

Within the last few years, the possibility of life has been supported by the conclusive evidence that the Martian polar caps are indeed crystallized water. The existence of life has actually been suggested by Sinton's findings of bands in the infrared reflective spectrum which have greater prominence in the dark, seasonally varying surface markings and suggest an accumulation of hydrocarbonaceous material in those regions and by Dollfus' findings of variation of the polarization, suggesting changes of granularity of those areas.

While it is of great fundamental interest to explore the detailed nature of these findings further from orbiting and flyby spacecraft, it is the capability for selecting the areas most promising for a detailed study from landed vehicles which may prove to have greatest significance. Infrared filter, grating, and interferometer spectrometers of various spectral ranges, spectral resolutions, and surface resolutions are under development at the present time for that and other purposes.

The detection of life on Mars and the determination of its properties is a prize of greatest scientific significance and is one of the prime goals of the U.S. planetary exploration programs.

At least four questions must be answered before the existence of Martian life can be established firmly.

1. How does it live?
2. What does it look like?
3. What does it eat?
4. What is it made of?

There is, of course, considerable temptation to concentrate on limited areas of the last two questions, on the hazardous and intellectually disappointing assumption that Martian life is similar to Earth-life. For example, it has been suggested that the response to a feeding of nutrients should be determined, or that DNA should be looked for, or proteins or certain enzymes, etc. While such experiments, if positive, would be tremendously exciting, the absence of general guidelines as to what nutrients to select, what enzymes to search for, etc., raises the possibility that such very specific first tests have a sufficiently low probability of succeeding to be wasteful of the precious spacecraft weight. On the other hand, the measurement of the environment and the miscroscopic examination of possible life forms may provide needed guidelines for subsequent more specific experiments. However, that approach may be wasteful of another precious commodity, time, since such a conservative program of experimentation may be considerably slower than the bolder, more direct approach discussed previously. At the present time, instruments and methods for all of the methods suggested are under study or development. No instruments have yet been selected for the first U.S. landing on Mars.

CONCLUSION

The deep space program provides an opportunity for tremendous scientific achievement. The traditional drive for scientific first discovery and experimental accuracy and precision is not incompatible with the present sharp atmosphere of international competition and, if the past can be used as guide, the contesting nations, groups, and individuals may well be spurred to exceptional performances.

With respect to the selection of experiments for deep space probes, it is essential that there be stimulated keen competition between potential experiments and experimenters. Complacency in the selection process based on arguments such as the following must be avoided.

(1) We know so relatively little about deep space it does not matter what experiments are performed. We may learn something from any of them.

(2) Since we want to know everything possible about deep space it does not matter which experiments are performed first. They will all be performed eventually.

(3) It does not matter what the experiment

is, only the reputation of the experimenter or of his organization need be considered.

The pursuit of excellence requires that there be standards which guide the selection process. The significance of the experiment with reference to the three crucial questions discussed is one of these standards.

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16. Interplanetary Space Physics

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INTRODUCTION

The physics of interplanetary space sounds almost like a contradiction in terms, as it has only been within the last five years that most of us have discarded the lifelong habit of preceding the noun "space" with the adjective "empty." In the new jargon of the space age, it has become customary to speak of "the interplanetary medium" and thus to emphasize its content rather than its emptiness. The medium is tenuous, however, the mean distance between atoms in it being several million times as great as in human tissue. The matter in space produces non-negligible effects, however, because it is ordinarily moving at extremely high velocities.

Interplanetary space physics is not very accurately defined as a scientific discipline. It attempts to answer questions like: What entities exist in space? What are their properties and behavior? What are their origins? In answering these questions, we immediately crowd the

boundaries of other disciplines. Thus, many of these entities come from the Sun leading us directly into the large and complex field of solar physics. Others may come from distant stars or galaxies, giving us an ill defined interface with the realm of the astrophysicist. If, then, we ask the question, "What effects do these entities produce?", we run smack into the physics of planetary atmospheres and ionospheres, geomagnetism, and meteorology. In this discussion, we shall avoid these latter problems by staying far enough away from the planets so that their presence does not disturb the phenomena of interest. It must be remembered that one of the most effective ways to study interplanetary entities has been, and in the space age still is, through the observation of their effects upon the Earth. This paper will deal chiefly with research done with instrumented spacecraft, as this is the primary concern of NASA and of the authors.

It should be clearly understood that this paper does not purport or attempt to present a comprehensive summary of the field of interplanetary space physics, which is, of course, as big as all outdoors. There exist summaries of small sectors of the field, such as galactic cosmic rays or solar-terrestrial relations, which are five or ten times the length of this paper. An incomplete list of such summaries is appended for the sake of the reader who wishes to pursue the subject in greater depth. We have frankly chosen to discuss a few, mostly interrelated topics in space physics in which the authors happen to be much interested even if not particularly expert. In so doing, we hope to convey some feeling for the kind of problems that occur, the kind of solutions that are attempted, and the excitement that we find in being a part of this great search for knowledge in an untrodden field.

To sample the interplanetary medium, it is necessary to go not only beyond the Earth's atmosphere, which extends only a few hundred miles for most practical purposes, but at least beyond the region where the geomagnetic field extends. According to the measurements of Explorers X and XII, this magnetosphere reaches 35 to 40 thousand miles in the direction toward the Sun and considerably farther in the opposite direction. For certain types of measurements, we shall have to go out hundreds of millions of miles—even out to the remotest planet or as close as possible to the Sun itself.

INTERPLANETARY FIELDS

Physics is concerned with the study of matter and energy, and entities belonging to both these categories are to be found not only in interplanetary space but, so far as we know, throughout all space. Energy may be associated with matter, or it may exist in the "pure" state which the physicist calls a "field." We shall have relatively little to say about fields in this paper, pleading the flimsy excuse that we are in the interplanetary spacecraft business at JPL, and one generally does not require an interplanetary spacecraft to study the fields which exist in space. One can easily think of exceptions to this generalization.

Interplanetary fields are both important and interesting. The gravitational field guides our spacecraft where we want them to go—or, more often up to now, where we do not want them to go. Spacecraft experiments have been proposed and will someday be carried out which may considerably increase our understanding of this most mysterious kind of field.

Electromagnetic fields have, until now, been almost our sole source of information about the universe beyond our atmosphere. Now, in the space age, we can exploit not only conventional visual astronomy but the equally fascinating fields of radioastronomy, ultraviolet astronomy, infrared astronomy, x-ray astronomy, gamma-ray astronomy—and people are even suggesting neutrino astronomy now with a straight face. For the most part, these sciences will be pursued from the Earth or from relatively near-Earth satellites, and this fact affords us an excuse to ignore them.

The magnetic field, however, cannot be ignored. The reason for this is simple and fundamental. Almost the entire universe is composed of and filled with what the physicists call a "plasma." A plasma is an ionized gas, an electrically neutral mixture of atomic ions and electrons, and it appears invariably to be associated with magnetic fields. Magnetic fields in some unknown but probably distant region of

the galaxy (or perhaps even outside) accelerate plasmas to extremely high energies to produce the cosmic rays. Other magnetic fields deflect the particles into curved paths, so that their lifetime in the galaxy is very long, and they appear to us to arrive isotropically from all directions. Other magnetic fields, probably associated with the Sun, modulate the intensity of the cosmic rays in ways that have yet to be explained. Yet, other magnetic fields, on the surface of the Sun, occasionally accelerate great showers of deadly charged particles and hurl them at the Earth, where still another field—the geomagnetic field—turns away these showers from the Earth or channels them into the vicinity of the magnetic poles.

The magnetic field of most current interest to the space physicist is the solar field. That the Sun is actually magnetic was first conjectured in 1878 at the time of a solar eclipse, when the resemblance of the coronal streamers to the lines of force around a bar magnet was first noticed. The lines can be seen in Figure 16–1, which was taken in 1918 near the maximum of the solar activity cycle, but they would be still more visible and more symmetrical near solar minimum.

It is possible, by measuring the Zeeman splitting of spectral lines, to measure the magnetic fields at the surface of the Sun (Ref. 1), but

FIGURE 16–1.—Solar corona, photographed at the total eclipse of June 8, 1918, Green River, Wyoming.

the technique is difficult and the results apply only to a single level and to a single component of the field. The only way to determine the shape and intensity of the field around the Sun appears to be to go there and sample it.

Although a variety of very sensitive magnetometers have been designed for use on spacecraft, so far only three truly interplanetary field measurements have been reported. The first was made by Lunik II in September 1959. The only thing that has been reported about this experiment (Ref. 2) is that the magnetic field close to the surface of the Moon does not exceed 50 to 100 gamma (which is 500 to 1000 microgauss). One can only speculate as to the reason for the surprisingly poor precision of this result, since magnetometers with 100 times greater precision are available.

The second measurement was made by Pioneer V, which had originally been designed as Venus fly-by spacecraft. Although it never got even close to Venus, it did gather an impressive amount of interplanetary data of several kinds, and it set a record for long-distance data transmission which even yet has not been surpassed. Pioneer V was launched on March 11, 1960 and last heard from on June 26, and in the intervening time it made approximately 40,000 measurements of the interplanetary magnetic field. Its magnetometer was of the simplest possible type—merely a wire solenoid wrapped around a slim cylindrical permalloy core. The current induced in the coil as the spacecraft rotated about its axis of symmetry was a measure of the field component perpendicular to the spin axis.

The orbit of Pioneer V is shown in Figure 16–2. During its active life, it traversed an arc of 105 deg about the Sun, always maintaining the orientation of its spin axis fixed in space as indicated by the arrow. The magnetic data which it yielded were of two kinds. One concerned the temporal fluctuations of the field; these will be discussed later in the paper when we are in a position to relate them to other data. The other concerned the normal undisturbed interplanetary field. It was observed that, in between the times when the field was relatively high and rapidly fluctuating, it frequently returned to a fairly steady value of approximately

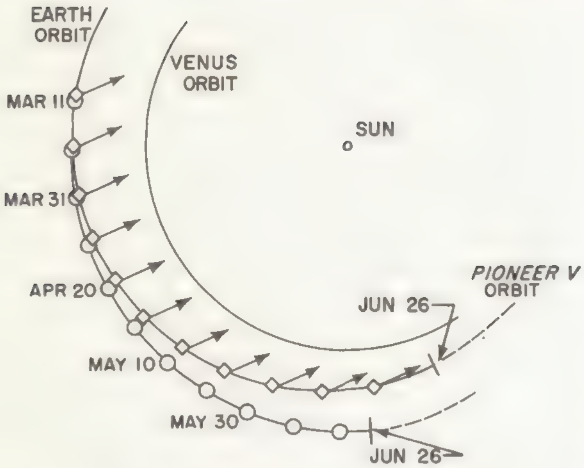

FIGURE 16–2.—Orbit of Pioneer V during lifetime of its transmitter. (Good magnetic data were obtained up to April 30. Arrows show projection on ecliptic of spin axis, which had right ascension 1 hr and declination 4 deg. Search-coil magnetometer measured maximum field component perpendicular to axis.)

3 gamma (1 gamma$=10^{-5}$ gauss). It was not possible to obtain any direct information about the direction of this field, but the fact that its magnitude did not change appreciably during the entire flight, while the angle between the spin axis and the sun changed considerably, appeared understandable only on the assumption that the direction was approximately perpendicular to the ecliptic (Ref. 3). This is, of course, precisely what would be expected if the solar field were like that of a dipole aligned with the Sun's rotational axis. Nevertheless, the result was at variance with the predictions of several different theoretical models, and many people have found it difficult to believe. We shall return to this point later.

After Pioneer V there was a long dry spell in interplanetary physics, terminated by the launching of Mariner 2 this August. Mariner does not spin, but maintains a fixed orientation in space. It carries a tri-axial flux-gate magnetometer, a considerably more sophisticated instrument than its predecessors, which measures all three components of the magnetic field every 37 seconds. As of the day before yesterday (when the scientific instruments were turned off temporarily), the number of such measurements that we have received from it is more than 140,000. The results appear generally to confirm the Pioneer V data, as the field component perpendicular to the spacecraft-Sun line is typically about 5 gamma at quiet times, and is inclined at an angle near 45 deg to the ecliptic plane. Unfortunately, Mariner 2 will not be able to give us the really definitive measurement of the interplanetary field for which we have waited so long. This fact results from our inability to separate the radial solar field from the component of the spacecraft magnetic field in the same direction. Only the sum of the two fields is measured, and its value also is typically about 5 gamma. We cannot rule out the possibility that the solar field component is actually several times this value but is cancelled out by an almost equal spacecraft component in the opposite direction. In the case of the other two components, it was possible to determine the spacecraft contribution to the field by taking data during the first few days of the flight, when Mariner was rolling slowly about an axis pointing toward the Sun.

We have considered the interplanetary magnetic field as an independent entity. This is an unwarranted simplification. Actually, the interesting and important physics of interplanetary fields deals with their interactions with matter. We will investigate these interactions in some detail after we have surveyed some of the kinds of matter that exist in space.

INTERPLANETARY MATTER

The Cosmological Problems To Be Solved

An understanding of the nature, origin, and dynamics of the small pieces of matter in interplanetary space is essential to the understanding of the origin and evolution of the solar system. There are at least three possible sources for these particles:

1. The disintegration of comets
2. The collisional fragmentation of larger solid bodies, such as the Moon, the asteroids, or other planetoids
3. Interstellar particles which move through the solar system

We may eventually be able to distinguish between cometary and planetary debris by studying the composition, density, and orbital characteristics of these particles. The measurement of the orbital elements alone should enable us

to distinguish whether a given particle is a member of the solar system or a brief visitor from interstellar space.

We will probably be able to determine the orbital properties of the very small particles (meteor size and smaller) before we have learned to make good measurements of density or composition. However, because of the great effect of the interplanetary environment on the motion of very small particles, a knowledge of the present trajectory of a dust particle in space does not necessarily allow us to know where it has been or what its future motion will be. The trajectory of a small particle is affected by solar electromagnetic radiation through the Poynting-Robertson drag force and by collisions with the particles in the solar wind. Furthermore, if the dust particle is electrically charged, there will be additional forces (Ref. 4) due to the relative velocity of the particle and the interplanetary magnetic field, which is probably being rapidly carried away from the Sun by the solar wind. The interpretation of a particle's history from a measurement of its present trajectory is further complicated because we do not yet have good estimates of whether or not a particle will be destroyed by sputtering by solar-wind particles before the orbit-changing forces just discussed have time to be effective (Ref. 5). Since the orbit-changing forces are relatively more important for small particles than for large ones, the measurement of the particle diameter and mass is also important.

Dust

Earth-based research in this area of cosmology has necessarily been concentrated on the study of meteorites, meteors, and comets. Rockets, satellites, and space probes now allow us to begin to study directly the still smaller members of the solar system.

Abundance and Mass Distribution. Prior to the availability of space probes, studies of dust particles entering the atmosphere had been carried out by means of visual and radar observations of meteor trails. From these data, an approximate curve showing the influx rate as a function of mass could be plotted, and the first

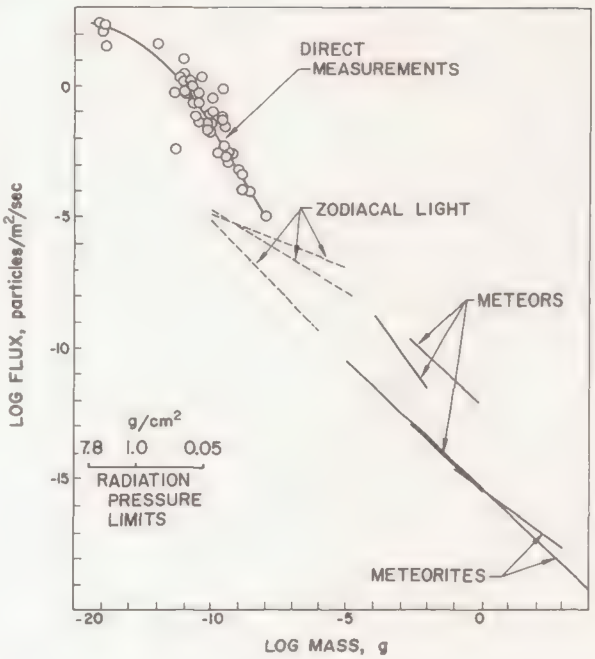

FIGURE 16–3.—Integral flux of meteoritic particles as a function of mass. (Compiled from Refs. 6, 7, 8, 9, and 10.)

dust experiments in space were aimed at extending the range of this function. Figure 16–3 (compiled from Refs. 6 through 10) summarizes some of the results of these studies. Several comments about this Figure are in order.

1. The extrapolations of most of the meteor and meteorite curves to particles of smaller mass give lower impact rates than those observed with rocket and satellite experiments; i.e., there is an excess of very small particles near the Earth.

2. The curves derived from zodiacal light data require assumptions about the physical nature and the distribution of the orbits of the particles which scatter sunlight to give the zodiacal light. Note that these curves fall considerably below the direct-measurement curves.

3. Most of the direct measurements have been made by accoustical methods in which the output of a crystal microphone is nearly directly proportional to the momentum of the impacting particle (perhaps with deviations from proportionality at the high velocities at which crater formation becomes important). To determine the impact rate vs mass function from data on impact rate vs momentum, one must assume a

velocity distribution for the particles. In drawing their curve, McCracken et al. (Ref. 6) assumed an average velocity which depends on the satellite orbit. If lower average velocities were chosen, the curve would be shifted to the right. If average velocity were a function of mass, the slope or shape of the curve would also change. Thus, measurements of velocity as well as momentum are being planned for future satellites and space probes. Since the McCracken et al. curve was derived from the data of many separate experiments, variations of impact rate with time and altitude might also tend to distort the curve; most of Cohen's Explorer VI data were obtained at a higher altitude than the data in the McCracken curve. Such variations will be discussed in more detail in a moment.

4. The radiation pressure limits refer to the smallest mass particle for which the gravitational attraction of the Sun is greater than the outward force due to radiation pressure. All lighter particles should be swept right out of the solar system; however, very small particles which scatter sunlight as Raleigh scatterers may remain. Since the radiation pressure limit is a function of the density of the particle, if we knew at what mass the impact rate vs mass curve became horizontal, we might have some idea of the density of these particles.

Spatial Distribution. The discrepancy between direct measurements of dust particles and that predicted from zodiacal light observations together with the slowly accumulating evidence that the directly measured impact rate depended on altitude have led to theoretical studies of why a concentration of dust might be expected near the Earth:

1. The gravitational potential well of the Earth-Moon system may act as a particle trap when the dynamics of the three- or four-body problem are considered. Some increase in impact rate as measured with a microphone is expected even without capture, because particles on hyperbolic orbits with respect to the Earth would be moving faster when near the Earth than when far from it, and smaller mass particles could therefore be detected.
2. Zodiacal particles may break into many smaller particles when near the Earth because of accumulation of a large negative charge when they are in the Van Allen Belts. If their structure were fairly fragile, they could be broken up by electrostatic pressure.
3. Particles may be captured into temporary orbits as a result of electrostatic or atmospheric drag.
4. When a meteoroid hits the Moon, many secondary particles may be able to escape because of the lack of a lunar atmosphere.

Figure 16–4 gives a summary of the data and theories (compiled from Refs. 11 through 14) on the variation of impact rate with distance from the Earth. Again, time variations and the possible variation of instrument mass threshold due to velocity dependence on altitude may cause the measured curve to give a misleading picture of the true altitude variation. Thus it is easily seen that a lot of both theoretical work and better, more thorough direct measurements are still needed before the true disturbance of the interplanetary dust distribution near the Earth is known and understood. Measurements are also desperately needed in deep space, away from the influence of the Earth; the first such results, from Mariner 2, may be published shortly.

Instrumentation. Most of the direct measurements of dust particles discussed so far were made with microphones. Other types of in-

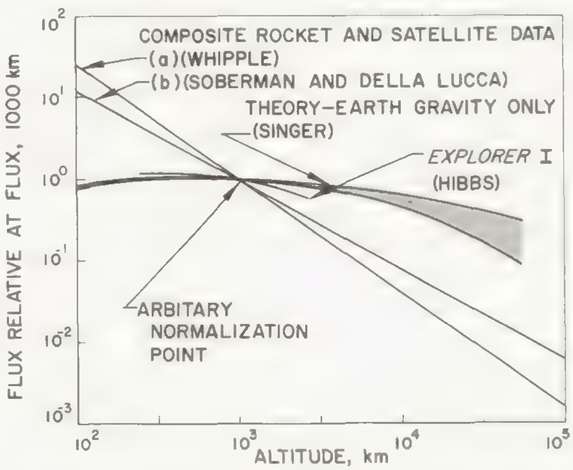

FIGURE 16–4.—Relative integral flux of dust particles as a function of altitude. (Compiled from Refs. 11, 12, 13, and 14.)

strumentation are slowly coming into use or are at least being experimented with to obtain a wider variety of information about the dust particles:

1. Detectors which measure the light flash generated when a particle impacts a solid surface have already been successfully flown on rockets and Earth satellites (Ref. 6). These instruments are capable of detecting much smaller particles than can be detected by acoustical methods.
2. Instrumentation has also been developed, but not yet flown, which generates an electronic pulse by collecting the ions produced when a dust particle penetrates a thin metal foil or impacts on a solid surface. The size of this pulse is a measure of the dust particle's mass and velocity if the particle is stopped.
3. The need for velocity measurements has already been stressed. Velocity can be found by measuring the time of flight over a known distance. The detection of the ion clouds just mentioned is one way of telling when the dust particle passed through a certain region of space.
4. The electric charge on a dust particle is important in determining the details of its trajectory, not only near the Earth but in the presence of the interplanetary magnetic field and streaming plasma. Several laboratories are developing instruments for measuring this charge by electrostatic induction; however, no charge measurements have been made in space yet.
5. Penetration and cratering studies have been made both on the ground and from satellites and rockets. The applicability of such measurements to the manned spaceflight program is obvious. The instruments flown to date, however, have in general been too insensitive to allow the accumulation of statistically significant results.
6. The recent Venus Fly Trap experiment captured some dust particles so they could be examined in the laboratory. Other, similar experiments will surely follow.
7. Another area for future measurements is in the determination of the composition of these very small particles. Composition is an important key to particle origin—cometary, asteroidal, or lunar. At least one group is working on the development of instrumentation for in-flight spectroscopy.

There is a lot of opportunity for new experiments which will determine the composition, density, or structure of dust particles.

Meteors and Meteorites

We have considered the dust particles in some detail because they are the subject of more active research and space measurements than the larger chunks of matter at present. The impact rate of particles large enough to produce meteors or meteorites is so exceedingly low that there is very little chance of their direct observation by a space probe for a flight of reasonable duration. This is a fortunate circumstance, for otherwise spaceflight might be impossible. The study of particles of this size is therefore presently limited to Earth-based research, with the possible exception of the study of crater distributions from a lunar orbiter. Current ground-based research on meteorites includes:

1. Age-dating and compositional studies to determine when and under what circumstances they might have been formed and how long they have been exposed to cosmic radiation.
2. A search for extraterrestrial life forms.
3. Studies of the erosion rate in space due to bombardment of the meteorite by dust particles and the solar plasma.

Comets

One of the most interesting and puzzling kinds of matter in space is the comets (see Figure 16–5). Mankind has always considered them to be mysterious—even sinister—because their appearance was generally unpredictable and because of their habit of unfurling their beautiful and awesome tails. Comets are incomparably less numerous than any of the other objects which we shall discuss, and no cometary particles are known to have been picked up on Earth, although the titanic explosion which devastated an area in Central Siberia in 1908 is believed to have been the impact of a comet.

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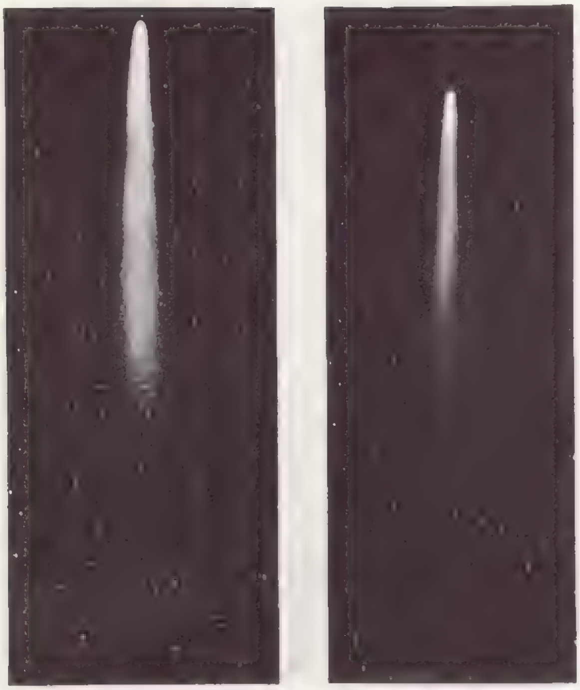

FIGURE 16-5.—Halley's Comet, May 12 and 15, 1910. (Tails 30 and 40 deg long. Photographed from Honolulu with 10-in. focal-length Tessar lens.)

The astronomers, whom we space physicists gladly acknowledge as predecessors and colleagues, have turned their telescopes and spectroscopes upon comets and their tails to inquire into their chemical composition and their motions. The spectra of the tails show the presence of carbon, nitrogen, oxygen, and hydrogen in various chemical combinations, from which it is concluded that a comet is an accretion of various condensed and frozen gases, such as cyanogen, carbon monoxide, and perhaps water—a kind of cosmic snowball. The tail is produced by matter evaporated by the heat of the Sun, ionized by ultraviolet light or some other agent, and then pushed away principally by the pressure of sunlight. The impact of solar proton streams also plays a part in comet-tail dynamics, as we shall see later.

The inaccessibility of comets to other types of investigation has led to a serious study of the possibility of sending a specially instrumented spacecraft to fly through the tail, or even to rendezvous with the comet head itself. The prime candidate for such a mission is Encke's comet, which has the shortest period of any recurrent comet—less than 3⅓ years. Carrying a mass spectrometer, a magnetometer, a plasma probe, a television camera, and perhaps an optical spectrometer, such a spacecraft could dispel much of the remaining mystery about the comets.

Interplanetary Charged Particles

There is another category of matter in space which is distinguished from that already discussed by the fact that electrical forces are predominant in determining its motions and their effects. This is the category of charged particles, including ionized atoms, electrons, and a sprinkling of less familiar sub-nuclear particles. They are frequently called "corpuscular radiation." In considering these, we enter a field in which the interplanetary space physicist, the solar physicist, and the astrophysicist are all deeply involved. The major bulk of these particles comes from the Sun, and we shall have to consider the nature of the Sun and its activity as a part of the problem.

Like the Earth, the Sun is made up of a number of concentric spherical layers. The one that we can see under ordinary circumstances is called the "photosphere" because most of the Sun's light is radiated from it. When we speak of the "solar radius," it is the photosphere's radius that is meant, and its value is 432,000 miles—considerably greater than the radius of the Moon's orbit about the Earth. The photosphere is a hot, very tenuous gas, having a temperature of 6000°C and a density of only 10^{16} atoms/cm^3, about 5000 times less than the density of the air around us.

If we take the radius of the photosphere as our unit of distance, then the chromosphere has a radius of 1.02. Having a relatively high calcium content, it can be made visible in the spectroheliоscope in calcium light. It is the source of some of the most remarkable of solar phenomena, to which we shall allude later.

Outside the chromosphere is the corona, normally invisible but showing up with spectacular beauty in a total solar eclipse. Its density de-

creases progessively with distance from the Sun, and it has no definite outer boundary, although it has been photographed during an eclipse out as far as 20 solar radii and other evidence shows that it extends more than twice that far. At 1.5 radii it contains about 10^7 protons and an equal number of electrons per cubic centimeter; a temperature above a million degrees Centigrade is indicated by spectroscopic and radioastronomical evidence. Such a temperature is, of course, too hot for ordinary atoms, and so the corona is completely ionized; that is, it is a plasma.

One might think that a plasma a million degrees hot surrounded by empty space would evaporate, and indeed something very similar to that apparently does happen. Sydney Chapman (Ref. 15) suggested in 1957 that the solar corona may extend out even beyond the orbit of the Earth at 215 solar radii, and this idea in several variant forms has become fairly generally accepted recently.

Chapman's initial attempt at a quantitative theory of the solar corona assumed it to be in static equilibrium, somewhat as the Earth's atmosphere is. Solving the differential equation for the flow of heat in a fully ionized gas, he showed that the temperature would fall off very slowly with increasing distance—inversely as the 2/7 power of the radius. Hence, if the inner corona were at two million degrees Kelvin, the temperature would still be 400,000 deg at the distance of the Earth. This result was surprising but not unbelievable, as the gas would be too tenuous to have much heating effect upon ordinary objects immersed in it. It was thought that its effect on the Earth's ionosphere might be significant, however.

A young Chicago physicist, Eugene Parker, was interested in Chapman's result and undertook to extend the theory. He showed that an immediate consequence of the slow fall-off in temperature was an even slower fall-off in pressure, so that even beyond the solar system, the solar corona would exert a significant pressure. Since it seemed clear that the intergalactic gas pressure is not sufficient to counterbalance this, the idea of an equilibrium corona had to be abandoned, and Parker (Ref. 16) replaced it with the idea of a constantly expanding corona.

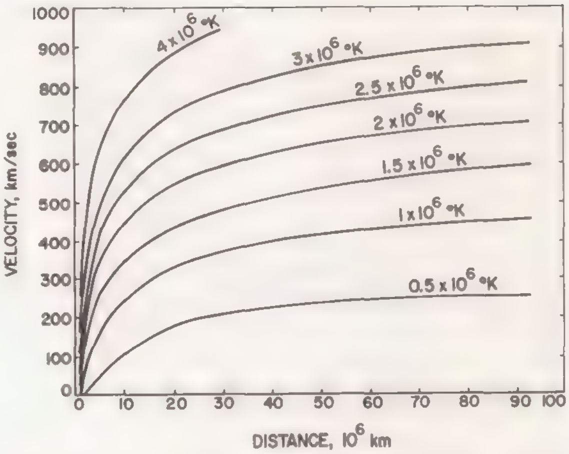

FIGURE 16–6.—Parker's spherically symmetric hydrodynamic expansion function, giving velocity as function of radial distance from Sun for an isothermal solar corona having specified values of temperature at unit radius, taken to be 10^6 km. (From Ref. 16.)

He assumed that some mechanism, which has not been clearly specified, maintains the temperature of the corona in the millon degree range out to some moderate distance like 4 solar radii, and that beyond that, the gas expands adiabatically. These assumptions gave a different set of equations, the quantitative predictions of which depended somewhat upon what values one chose for certain parameters which are difficult to evaluate. The general results are shown in Figure 16–6, where the expansion velocity of the gas is plotted as a function of distance from the Sun. The units on the horizontal axis are approximately 1 solar radius. It is seen that one can get almost any velocity by selecting the proper temperature for the inner corona, as indicated on the various curves. Parker himself favored a temperature in the neighborhood of 1.5 million degrees, giving an expansion velocity at the Earth of around 500 km/sec. He termed his theory the "hydrodynamic" theory of the solar corona, and for the high-velocity gas flow which it predicted, he coined the picturesque term, "the solar wind."

Parker's is not the only theory of the corona, but it has probably stirred up more interest and discussion in recent years than any of its competitors, and it has recently received a striking confirmation, as we shall see. A velocity of 500 km/sec was favored for the solar wind be-

cause this velocity had been postulated by Ludwig Biermann on the basis of his study of comets. Here is another of the many examples where the astonomers have gotten a good start on a problem which must now be followed up by the space physicist.

All of us learned that the tails of comets point away from the Sun, impelled by the pressure of the light of the Sun. For some comets, this may actually be true. But Biermann (Ref. 17) studied in detail the motion of a certain class of comet tails (called Type I). By measuring the acceleration of knots of matter in the tails, he showed that the forces being exerted on the tails were far greater than could be explained by light pressure. The measurements could not be made with great accuracy, but Biermann suggested that the accelerations could be explained by the interaction of the atoms of the tail with a stream of plasma having a density of about 100 protons/cm^3 and a velocity of about 500 km/sec. Since comet tails are always observed to be accelerated away from the Sun, the Sun must be sending out streams of plasma in all directions all the time.

Other indications pointed to the possible existence of a steady solar wind, although they did not yield much idea of its magnitude. In an annular zone around the two magnetic poles, aurorae are seen every night, and as the accepted explanation of aurorae is that they are produced by the impact of charged particles from the Sun, the particles must be produced continually. The existence of continual fluctuations in the geomagnetic field near the poles also indicates that solar plasma may be bombarding the top of the magnetosphere at all times.

The idea that interplanetary space is not empty but is, in a sense, full of solar plasma has grown gradually over several decades. We shall trace this growth briefly later. But first, let us point out how completely different is the physics of space when based upon these two pictures. If space is empty, then the magnetic field of the Earth can be represented as a dipole field, as shown in Figure 16–7. Its intensity falls off gradually with distance until it reaches a magnitude of a few microgauss and merges smoothly and imperceptibly with the field of the Sun's dipole. The effect of localized magnetic disturbances on the surface of the Sun does not extend far from the Sun, so that space near the Earth is magnetically quiet. The Sun's dipole field merges calmly with the even weaker galactic field at some large but unknown distance. The paths of charged particles in space, whatever the particle energies might be, can be calculated on the basis of the theory of Störmer (Ref. 18) which was published in 1907. All that we need to know for most purposes are the magnetic dipole moments of the Earth and the Sun. If charged particles are ejected by the Sun, they will reach the Earth along fairly

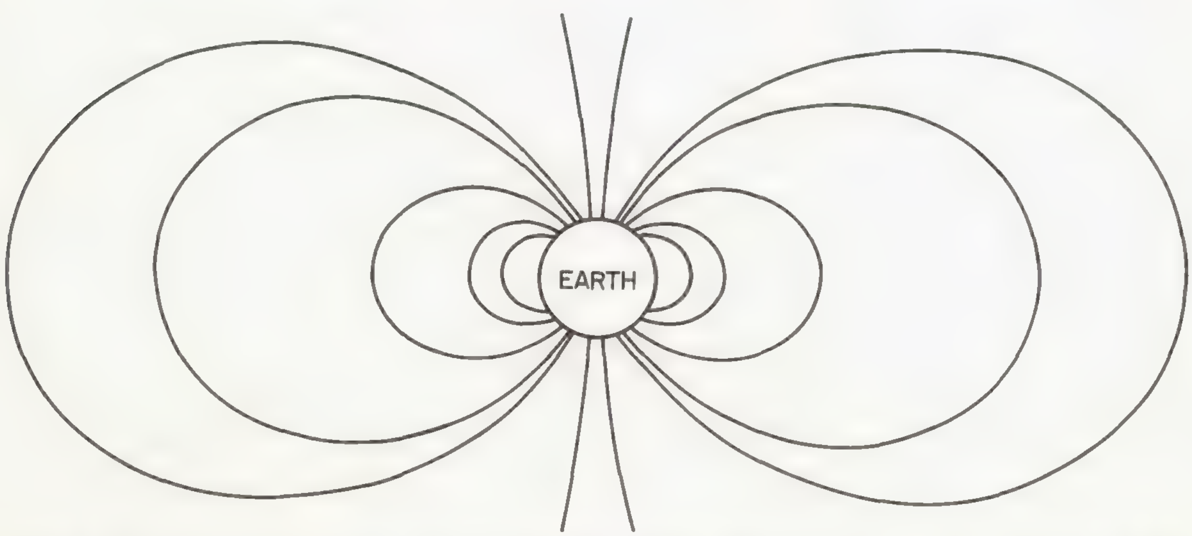

FIGURE 16–7.—Representation of field lines of geomagnetic dipole, assuming empty space surrounding the Earth.

simple and direct paths, with their time of arrival at the Earth depending only upon their velocity (or more accurately, on their magnetic rigidity). In short, the physics of space is electrodynamics, the theory of which is about a century old.

If space is full of plasma, then its physics is magnetohydrodynamics, the theory of which dates essentially from 1950. The physics of plasmas (Ref. 19) is most strikingly characterized by one all-encompassing effect—the intimate coupling of particle motion and magnetic fields. When the electrical conductivity of the plasma is high (as it is in space), the magnetic field is able to diffuse through the plasma so slowly that it is customary to say that the magnetic field lines are "frozen into the plasma" (Ref. 20). A consequence of this coupling is a simple and convenient general rule which is helpful in predicting the gross features of the motion of a plasma. The rule is this: The nature of the plasma motion depends upon whether the particles or the fields are in command. A plasma contains three kinds of energy: (1) magnetic energy, which depends upon the magnetic flux density B; (2) the energy of the random motion of the particles, which is thermal energy and proportional to the temperature T; and (3) the energy of bulk motion of the plasma, the kinetic energy, which depends upon the velocity V. We wish to compare the energy densities or the pressures of these three kinds, so we include the particle density n in the formulas.

$E_{mag} = 4\ B^2$ (B in γ)
$E_{therm} = 138\ nT$ (T in 10^6 deg K)
$E_{kin} = 0.0084\ nV^2$ (V in km/sec)

(n in particles/cm^3)
($\gamma = 10^{-5}$ gauss)

Now, if the magnetic energy is dominant, the particles are confined to move with the field lines; this is the case very close to the Earth, where plasmas are trapped in the Van Allen Belts. If the thermal energy is dominant, the field lines are constrained to move with the particles; this is the usual case in the Sun. If the kinetic energy is dominant, a cloud of plasma can move along almost as though it were solid, carrying its magnetic field lines trapped within it; this, as it turns out, is apparently the case in the outer corona, where the Earth is.

With all this magnetohydrodynamics under our belts, let us go back and look at interplanetary space. It now looks quite different. With a plasma present, the geomagnetic field cannot look like the simple dipole that we saw in Fig. 16–7. At large distances, its energy density becomes too low, and the geomagnetic field is replaced by the field of the interplantetary plasma, as shown in Figure 16–8. (This particular picture happens not to depict the Earth; it shows Venus, with Mariner passing by.) The transition might be expected to be rather sharply defined, and it has come to be known as the "magnetopause." Outside it is the interplanetary plasma; inside it is a kind of bubble where the plasma cannot penetrate. Whether this bubble actually exists and what its shape may be are among the most exciting problems of current interplanetary space physics.

Outside the magnetopause, we will now see not the main dipole field of the Sun but the trapped field of the plasma—unless, of course, the plasma is very weak. If the solar wind exists, it will carry part of the solar field with it and stretch out the lines so that they will be radial near the Earth, or nearly so. The more accurate picture, as shown in Figure 16–9, is an Archimedean spiral, which results from the fact that the field lines are carried around by the rotation of the Sun. This is precisely analogous to a rotating lawn sprinkler, which squirts water out radially but makes a spiral pattern in the air at any instant of time. We call this the "garden hose effect." It may also be that the solar wind is not smooth and regular but turbulent, in which case the magnetic field lines trapped within it will get all knotted up. Parker's theory predicts that this must occur at some large distance from the Sun, probably well beyond the Earth's orbit.

Before we turn to experimental physics, one final reference to plasma theory. We all know that objects traveling in the atmosphere faster than sound push a shock wave ahead of them. Some of us have had our windows broken by these supersonic booms. In a plasma, there can exist a bizarre kind of wave that is named for its discoverer. In the units we are using, this

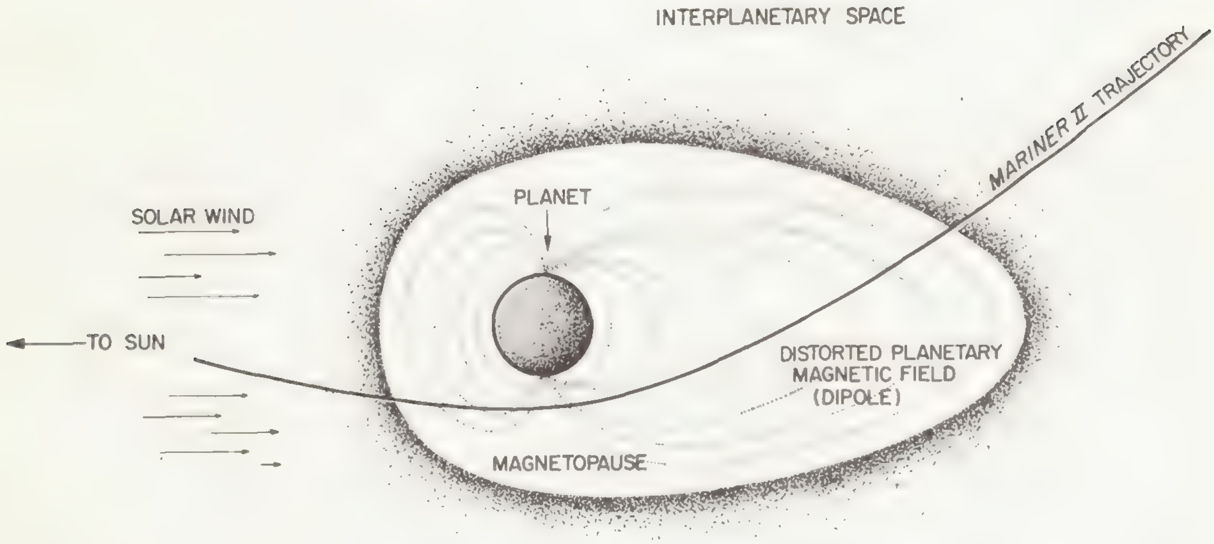

FIGURE 16–8.—Representation of possible shape of field lines of geomagnetic dipole as distorted by solar wind. (Shape of magnetosphere is highly conjectural, particularly in antisolar direction, and actual situation is considerably more complex than indicated.)

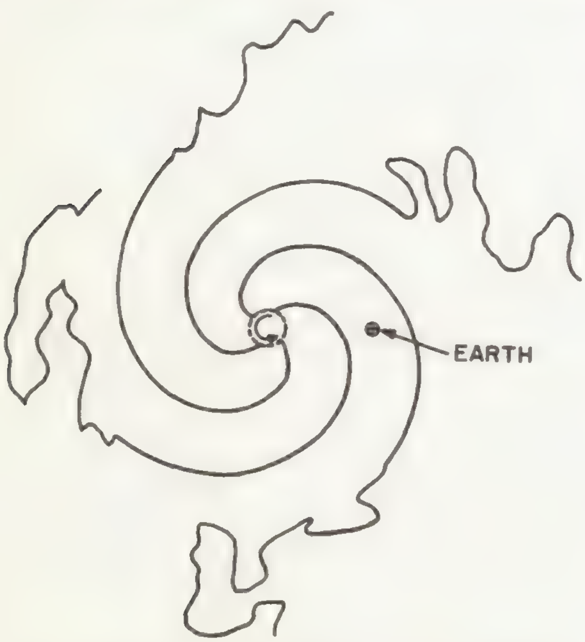

FIGURE 16–9.—Hypothetical shape of solar equatorial magnetic field resulting from radial solar wind, showing "garden-hose effect" and onset of turbulence at large radii.

Alfvén wave velocity is $W = 22B/\sqrt{n}$ km/sec. If an object is moving faster than the Alfvén-wave velocity, the situation is analogous to that of supersonic flow. So, if it should turn out that the solar wind is supersonic—or more accurately, super-Alfvénic—then the Earth should have a shock wave. The picture in Figure 16–10 has just been published by W. I. Axford (Ref. 21) in a theoretical discussion of this point. The Earth is the tiny circle in the center, and the blob shaped like an airfoil is the magnetosphere. The top diagram depicts a section through the magnetic poles, and the bottom one is an equatorial section. In either picture, we see the solar wind coming in supersonic, being slowed to subsonic speed on passing through the detached shock front, and then traversing a sonic surface, where it is accelerated to supersonic again and proceeds on its way. Note that none of it penetrates the magnetopause. The actual observation of this shock wave will be an exciting confirmation of the theory.

When the availability of space probes became imminent, several groups of physicists began making plans to study the solar wind directly. A Russian group, headed by K. I. Gringauz, designed what they call "trielectrode traps" (Ref. 22), which they flew on the first, second, and third "Cosmic Rockets" and on the ill-fated 1961 Venus probe. A diagram of the instrument is shown in Figure 16–11. Four

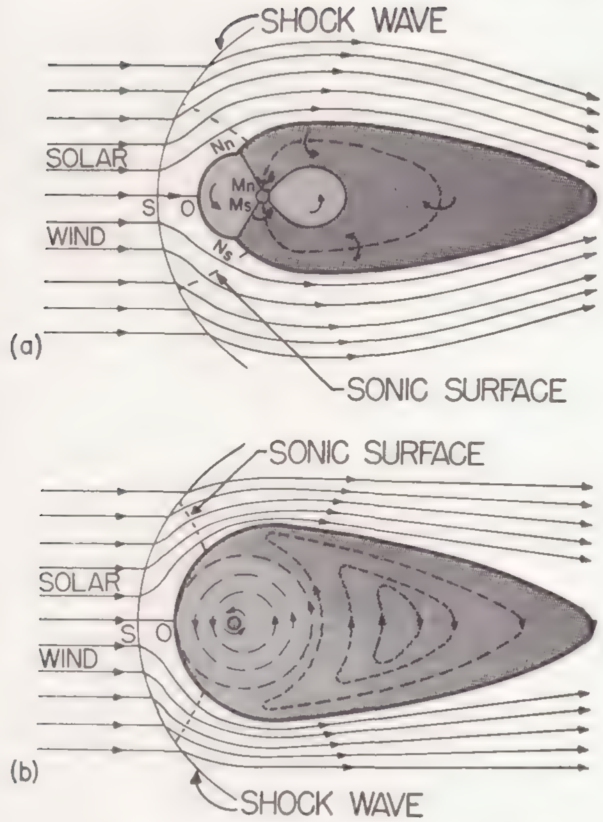

FIGURE 16–10.—Magnetosphere in a "supersonic" solar wind. (Diagrammatic sections (a) in plane of geomagnetic axis and solar-wind direction, and (b) in geomagnetic equatorial plane looking from above North pole. Geomagnetic tail is indicated by shading and sense of rotation of magnetosphere by short arrows. Lines outside magnetosphere represent streamlines of solar wind, and bow shock wave is shown on upstream side of magnetosphere. Flow behind shock wave becomes supersonic as it passes through sonic surface, roughly in position indicated by lightly dotted lines. From Ref. 21.)

of these were distributed symmetrically over the approximately spherical surface of the *Lunik* instrument containers. The outer screens of the four were held at four different very low voltages, so as to give some information about the identity and energy of collected particles. The inner screens were at 200 volts negative potential to suppress photoelectrons. The collector plates were held at 60 to 90 volts, and positive or negative currents collected on them were measured. Currents could be measured only in a very restricted range above 10^{-10} amp.

A disappointingly small amount of useful

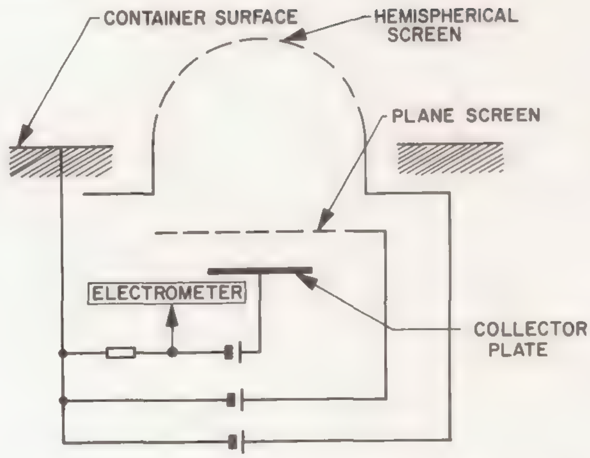

FIGURE 16–11.—Schematic diagram of Russian trielectrode ion trap as flown on Luniks. (From Ref. 22.)

scientific information has come from these experiments. So little has been published about them that it is hard to ascertain whether this is attributable more to bad luck or to bad judgment. Their range of current measurement—a factor of 50—compares very poorly with the millionfold range of comparable American instruments. Their energy resolution was extremely poor at low energy and nonexistent at high energy. Finally (I quote from Gringauz' original publication in English translation), "while traveling along the trajectory, the container with the scientific apparatus made intricate, rapid rotational movements. Due to this fact, the orientation of each trap relative to the velocity vector and the Sun direction continuously changed which caused corresponding fluctuations in the collector currents" (Ref. 23). The result is that the data are extremely hard to interpret unequivocally.

Gringuaz summarizes the findings as follows (Ref. 23):

1. Lunik II, in September 1959, detected a stream of positive ions between 40 Earth radii and the Moon having energies exceeding 15 electron volts; the flux was approximately 2 x 10^8 per square centimeter per second.
2. These results were confirmed by Lunik III the following month.
3. During 20 minutes of radio contact with the Venus probe in February 1961, at 1,890,000 km from the Earth, a flux of

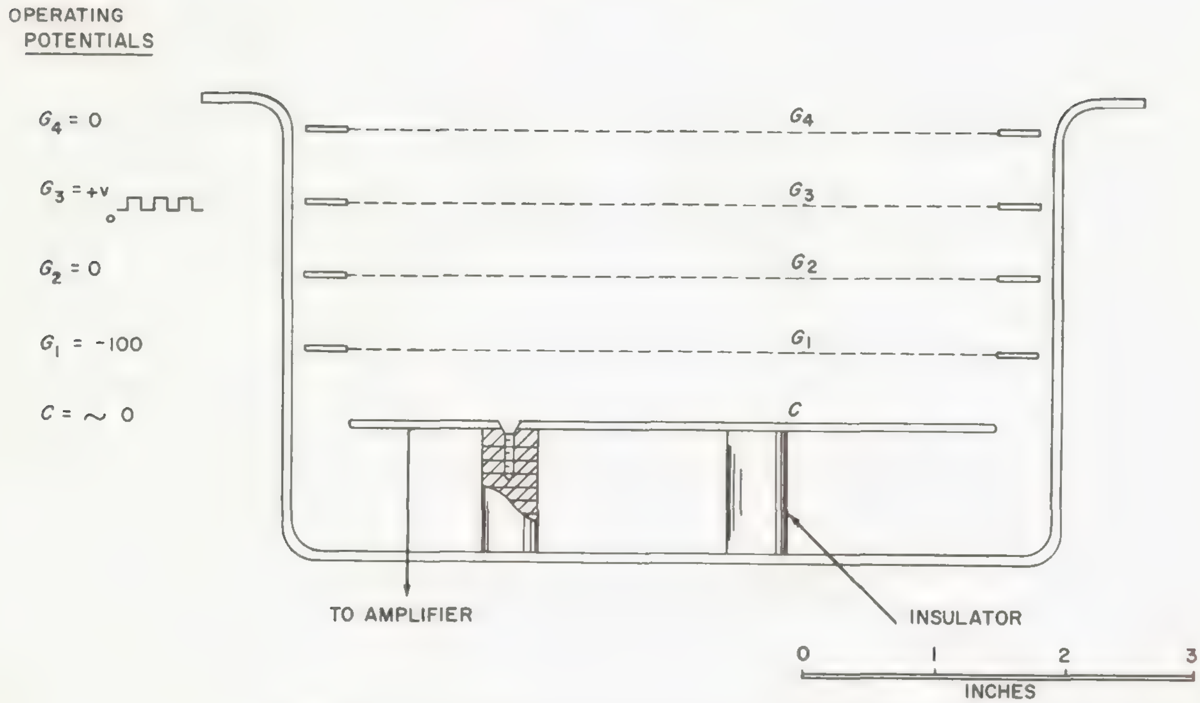

FIGURE 16–12.—Explorer X plasma probe. (From Ref. 25.)

positive particles equal to about 10^9 per square centimeter per second was observed. E. R. Mustel of the Astronomical Council of the Soviet Union was quoted in the press (Ref. 24) as indicating that the Venus probe showed "that the outflow of gas from the Sun is largely sporadic during solar storms, and if there is a steady solar wind it is extremely slight."

The next group which got a chance to try to observe the interplanetary plasma was the MIT group headed by Bruno Rossi. One month after the Russian Venus probe, they launched a plasma detector on Explorer X. Shown in Figure 16–12, the instrument was a multi-grid Faraday cup, considerably more sophisticated than its Russian counterpart (Ref. 25). A square-wave modulating voltage was impressed on Grid No. 3, which served to eliminate the effect of photoelectrons and to give a rough energy measurement of the positive ions. The modulating voltage was changed periodically to measure ions of different energy, and a complete five-point spectrum was obtained every 20 minutes. Three magnetometers built by J. P. Heppner (Ref. 26) of the Goddard Space Flight Center were also aboard, and the space probe transmitted data for 58 hours, out to about 42 Earth radii.

The data received from this spacecraft were of excellent quality and interesting, but rather puzzling. The plasma probe suddenly began detecting plasma at a distance of 22 Earth radii, and thereafter, at intervals of a few minutes or a few hours, the plasma disappeared and reappeared. When it was present, the magnetic field was weak and fluctuating; when the plasma was absent the field was strong and steady. The data were consistent with the direction of motion of the plasma being radial away from the Sun but the field of view of the plasma probe was very large so that this direction could not be determined with precision.

The probable explanation of these data is shown in Figure 16–13 (Ref. 27). The trajectory of Explorer X was generally in the direction of the Earth's shadow and apparently lay, quite by accident, right along the boundary of the magnetosphere. The position of this boundary changed occasionally, in response to changes in the solar wind, and swept back and forth across the probe, sometimes shutting out the plasma and sometimes allowing it to reach

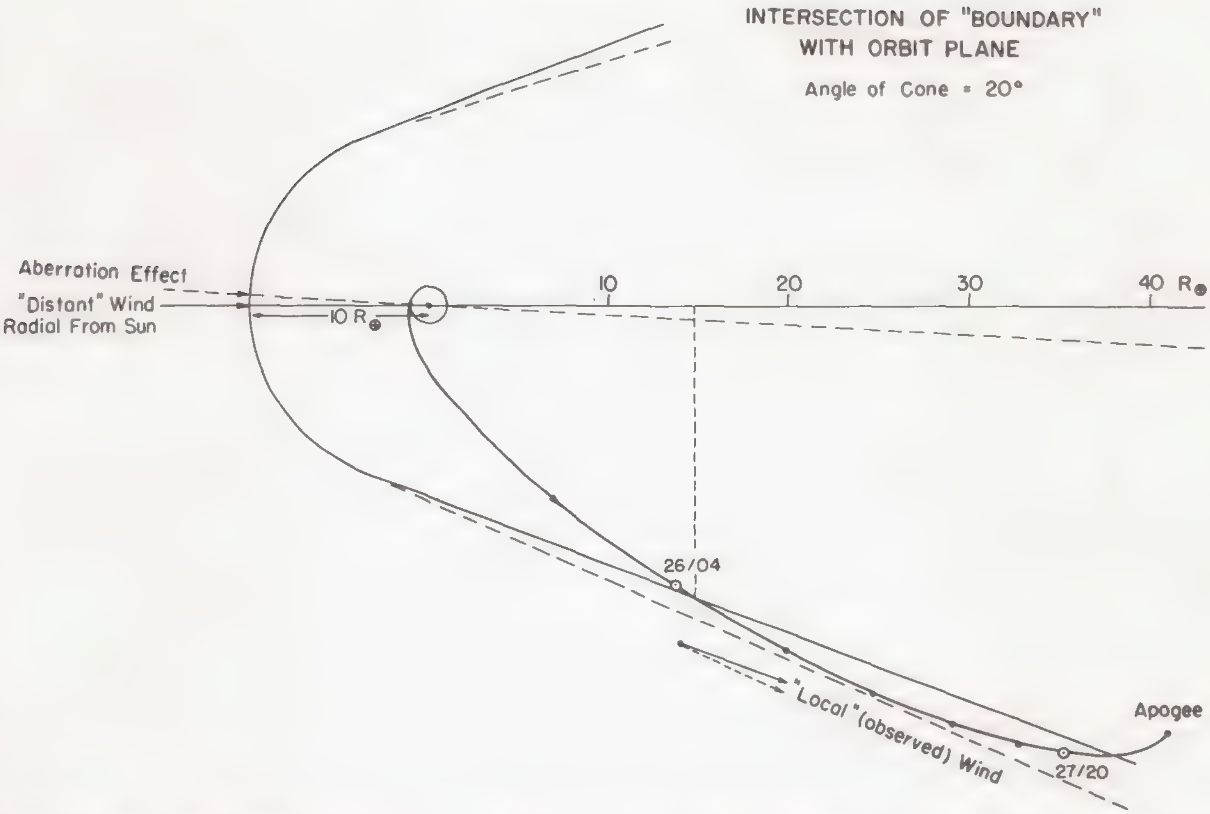

FIGURE 16–13.—Explorer X trajectory and intersection of magnetopause with plane of trajectory, assuming solar wind moving radially from Sun. (From Ref. 27.)

the detector. The energy of the plasma was principally between 250 and 800 electron volts, with very little above or below this range. The plasma density was indicated to be about 10 protons/cm^3, and the velocity about 300 km/sec. This result is of great interest, and seems to confirm the solar-wind idea. However, it means that Explorer X was not really an interplanetary probe, since the plasma adjacent to the boundary would have its density, velocity, and direction of motion distorted by its encounter with the magnetosphere. For a detailed study of the undisturbed solar wind (if any), we had to try again.

Five months later, in August 1961, Explorer XII was launched into an elongated elliptical orbit extending toward the Sun. It carried a plasma probe, built by Michel Bader of NASA's Ames Research Center, which included an electrostatic particle-energy analyzer, so that it could make much more detailed measurements of the plasma energy and velocity than either the Gringauz or the Rossi probes had been able to do. Unfortunately, this instrument did not detect any plasma, for reasons which are not clear, and it has not yet been flown successfully. The magnetometer, supplied by Laurence Cahill of the University of New Hampshire, produced data for 16 weeks, and it clearly delineates the position and breadth of the magnetopause on numerous traverses through it (Ref. 28). The position is at 10 or 11 Earth radii on the sunward side of the Earth during magnetically quiet times and somewhat closer at disturbed times, apparently because the solar wind is stronger then. The breadth of the magnetopause is variable, between 100 and 1000 km. Inside it, the Earth's magnetic field is about twice as strong as it would be in the absence of the solar wind, being compressed by the momentum of the incident plasma.

The apogee of Explorer XII was at 13 Earth radii. At this distance, the magnetometer detected a field of 30 or 40 gammas, which is al-

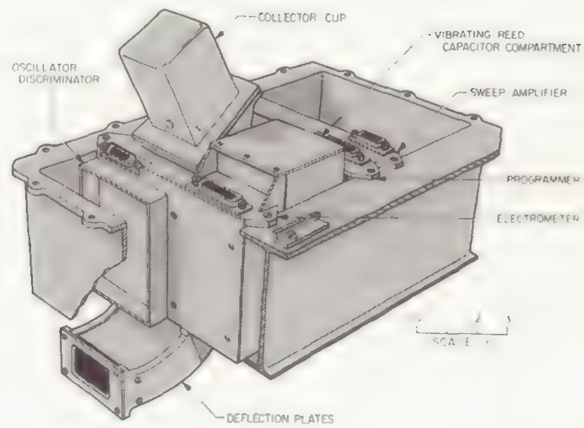

FIGURE 16–14.—Mariner 2 plasma probe.

most certainly too high to be the true interplanetary field. Apparently the presence of the magnetosphere is controlling the situation at all points on the trajectory. Thus, although Explorer XII contributed very important clues to the nature of the interplanetary plasmas, it still did not sample them directly.

Our first three attempts to do a genuine interplanetary plasma experiment were thwarted by malfunctions in the booster rockets, but finally came Mariner 2. Up to now, it has given us 63 days of almost continuous data. Its plasma probe was built under the direction of Marcia Neugebauer and Conway Snyder of JPL. The magnetometer experimenters are Paul Coleman and Charles Sonett of NASA, Leverett Davis of Caltech, and Edward Smith of JPL.

The solar-wind detector, shown in Figure 16–14, is an electrostatic analyzer, identical in principle but very different in detail from the one on Explorer XII. Charged particles which get through the aperture find themselves in a cylindrical electric field between the two deflection plates. The field sorts out the particles and allows those with the proper energy and the proper direction of motion to reach the collector. The current carried by these particles is measured by a sensitive electrometer circuit, and the resulting data are sent to the spacecraft telemetry system. The electric field is progressively changed through ten different values, so that each 222 seconds a complete ten-point energy spectrum of positively charged particles is obtained. In the same length of time, the fluxgate magnetometer, having a sensitivity of less than 1.0 gamma, measures the three components of the magnetic field six successive times. This time, there was no question that we would be doing a truly interplanetary experiment, as the instruments were not even turned on until the spacecraft was 450,000 miles from the Earth on its way to Venus.

Because of the very stringent weight limitations on our first-generation interplanetary spacecraft, the capabilities of the plasma detector had to be rather arbitrarily restricted, so that to fly it was something of a gamble. We assumed that the solar wind would most likely be moving radially outward from the Sun, and pointed our detector directly toward the Sun, taking the risk that we might detect little or nothing at all if the actual direction were as little as 10 deg from radial. We guessed that the solar-wind velocity would be high, on the basis of Parker's theoretical predictions and the results of Explorer X, and we set our lowest level of detection at 230 electron volts, corresponding to proton velocities of 210 km/sec. If the solar wind velocity were above about 200 km/sec, and below about 1250 km/sec, and if it were blowing radially outward from the Sun, then we hopefully expected to see it.

This time our luck was better. We have as of today measured the energy spectrum of the solar wind 23,500 times, and the velocity appears always to be between 380 and 690 km/sec, with no very marked preference for any particular value in that range. Clearly, the solar wind is blowing continually and radially, for it has been detectable in every single sweep of the spectrum which we have yet examined; there was only one period of a few minutes

when its intensity was so low as to be barely above the minimum current sensitivity of the instrument. We are only beginning to understand what this mass of data has to tell us, and much hard work of analysis lies ahead.

Future spacecraft, carrying multiple plasma detectors with greater sensitivity, greater energy resolution, and with the capability of measuring the direction of motion of the solar wind will greatly extend our understanding of it. In particular, the question as to how far out from the Sun this extension of its atmosphere extends is of great interest and may take several years to determine.

Two very significant qualitative conclusions about the nature of the interplanetary medium can be drawn from the combined data of Pioneer V, Explorer X, and Mariner 2. Assuming reasonable values for the pertinent quantities, we may take

$$B = 10 \text{ gamma}$$
$$n = 10 \text{ ions/cm}^3$$
$$V = 400 \text{ km/sec}$$

Then, using our formulas, we have

$$\frac{E_{KIN}}{E_{MAG}} = \frac{0.008nV^2}{4B^2} = \frac{13{,}000}{400} \simeq 30$$

which tells us that the particle energy dominates the field energy, so that the magnetic lines of force are carried along in the plasma cloud. Also,

$$\frac{V}{W} = \frac{V\sqrt{n}}{22B} = \frac{400}{70} \simeq 6$$

which tells us that the solar wind is effectively "supersonic," so that shock-wave effects are to be expected.

SOLAR DISTURBANCES AND THEIR EFFECTS

Up to this point, we have been discussing the Sun and its surrounding space as though nothing ever happens in it. Such is by no means the case. We have all heard of sunspots, and some of us have even seen them. They have been known and studied for a very long time, as Figure 16–15 attests. In it, we see a record of the well-known eleven-year sunspot cycle (Ref. 29). The last few years have been particularly interesting in this regard, because we

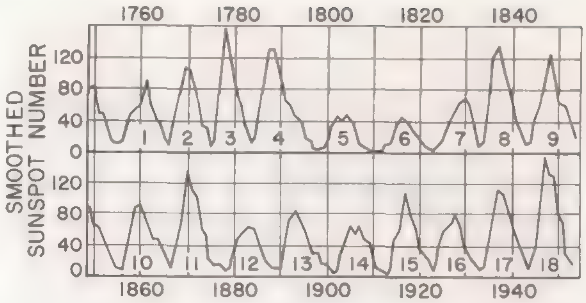

FIGURE 16–15.—Sunspot data available since 1750. (Note fairly steady increase in intensity during present century. From Ref. 29.)

have much better instruments and techniques for studying the Sun than ever before and because the Sun appears to have been especially active. In fact, the sunspot number reached an all-time high of 355 in December 1957. We shall not linger on the subject of sunspots except to point out that there are a number of occurrences on Earth which appear to correlate well with the number of sunspots, and that one of the most striking of these is magnetic disturbances. This correlation is shown in Figure 16–16 (Ref. 30).

Sunspots are only one manifestation of disturbances on the Sun, which occur not only in the photosphere where we see the spots, but in the chromosphere, in the corona, and certainly in parts of the invisible interior as well. Other types of solar disturbances include *plages*, which are large bright areas that always surround sunspots or sunspot groups, *prominences* (see Figure 16–17), which appear to be projections of the chromosphere into the corona, sometimes as high as 100,000 miles, and *chromospheric flares* (see Figure 16–18). All these

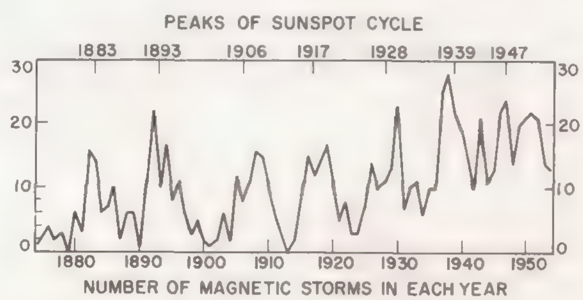

FIGURE 16–16.—Number of geomagnetic storms observed in each year. (Note correspondence between peaks and times of peak sunspot number, shown at top. Adapted from Ref. 30.)

FIGURE 16–17.—Solar prominences. Photospectroheliograph of the whole edge of the Sun, taken with the calcium K line, December 9, 1929.

phenomena appear to be related in some way, all involve rather intense local magnetic fields, and their elucidation is one of the outstanding current problems of solar physics. To the interplanetary space physicist, the flares are of the greatest interest.

A solar flare is a catastrophic disturbance, probably basically magnetic in character, which appears suddenly, decays gradually, and usually is gone within an hour. A few flares are visible in white light, but ordinarily it requires a spectrohelioscope using the red line of the hydrogen spectrum to make them visible. When observed through this instrument, they are spectacular phenomena indeed, as an area perhaps one thousandth the size of the solar disk may suddenly increase in brightness by a factor of ten. A large flare may involve as much energy in its 1000-sec lifetime as the entire Sun radiates in a second, and the emission of light is not the only phenomenon it manifests, as we shall see.

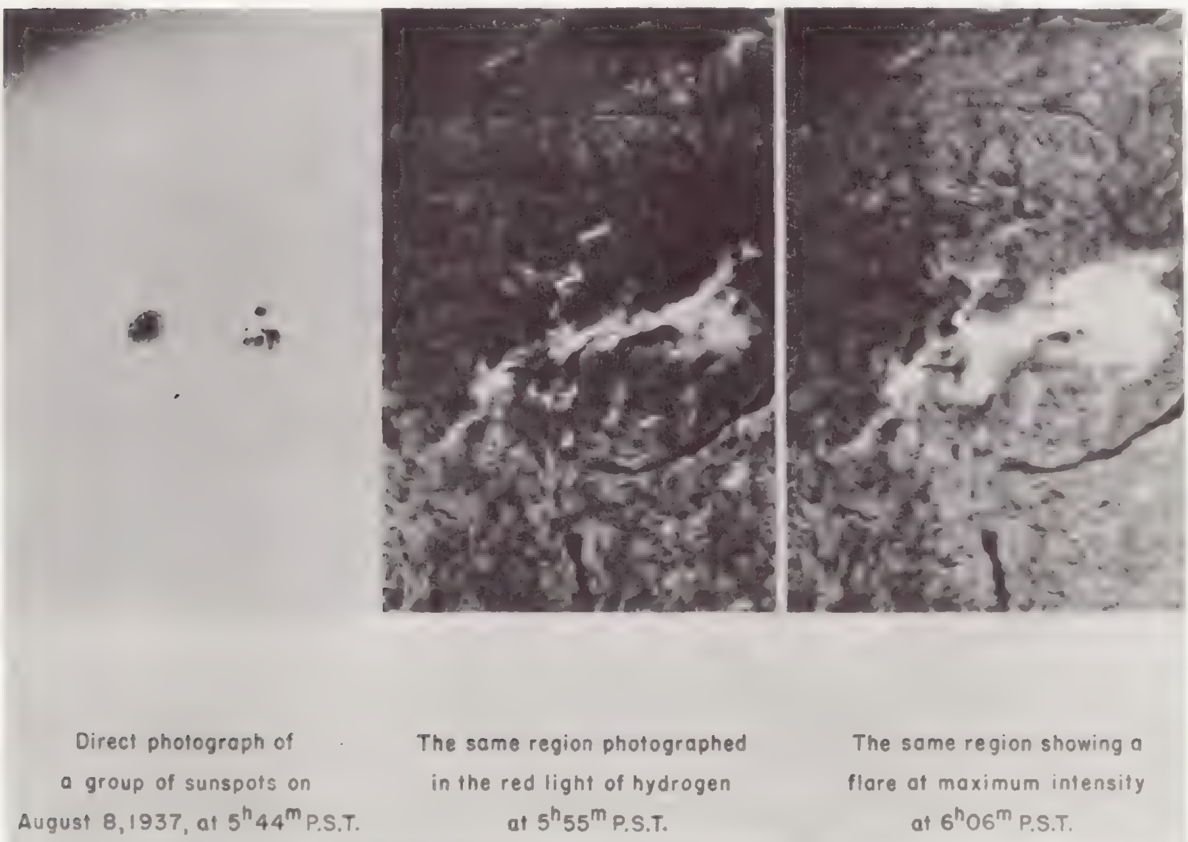

FIGURE 16–18.—Sunspot group and associated flare.

Turning now from the Sun to the Earth, we note that the geomagnetic field is not constant and quiet but is subject to both regular variations and irregular disturbances. When these disturbances are large, they are called geomagnetic storms, and they may be of interest to people who are not geophysicists because of their disruption of radio communications and their production of intense aurorae at high latitudes. We have already noted that the frequency of these storms is strikingly correlated with the sunspot number. An explanation of this effect was proposed by K. Birkeland (Ref. 31) in 1896. He suggested that the Sun occasionally emits a stream of electrons, which distorts the geomagnetic field upon entering it. In 1911, Schuster criticized this theory on the grounds that a beam of electrons could not hold together against the mutual electrostatic repulsion of the particles, but Lindemann, in 1919, disposed of this objection by suggesting that the streams might be ionized but electrically neutral—in other words, that they are streams of what we now call plasma (Ref. 32).

In the 1930's, Chapman and Ferraro, in a series of classic papers (Ref. 24), worked out the details of the theory of the interaction of such a plasma stream with the geomagnetic field, and established the idea on a firm foundation. This theory, as well as that of Alfvén (Ref. 19), and others, assumed the emptiness of interplanetary space. With the emergence of the notion that space is permeated with plasma, it became clear that some changes were required in the theory. Clearly, a sudden disturbance in the geomagnetic field can be caused only by some sudden change in the solar wind, if the solar wind exists.

Pioneer V did not carry a plasma detector, and thus it gave a rather incomplete picture of what the interplanetary medium was doing; but it did clearly establish the fact that the interplanetary magnetic field is frequently disturbed, and that these disturbances correlate with both solar and terrestrial events. A 50-day section of the Pioneer V magnetic record is shown in Figure 16–19 (Ref. 3). Fluctuations in the field are clearly the rule rather than the exception. Correlations between the interplanetary field and geomagnetic conditions as summarized by the planetary magnetic index a_p are shown in Figure 16–20 (Ref. 33). A comparison between the amount of flare activity on the Sun and the Pioneer V data is presented in Figure 16–21. Because of the time required for the disturbances to propagate from the Sun out to the orbit of the spacecraft, the correlation is improved by introducing a two-day shift in the time scales of the figure. Several of the larger magnetic fluctuations showed striking and significant correlations with the readings of the particle counters on the spacecraft; these will be discussed later.

Similar phenomena are observed on Mariner 2, but now the presence of the plasma detector makes it possible to observe in some detail what the solar wind is doing when the magnetic field fluctuations occur. The number and variety of these fluctuations is so great that we are barely beginning to understand them. One particularly interesting example will be discussed.

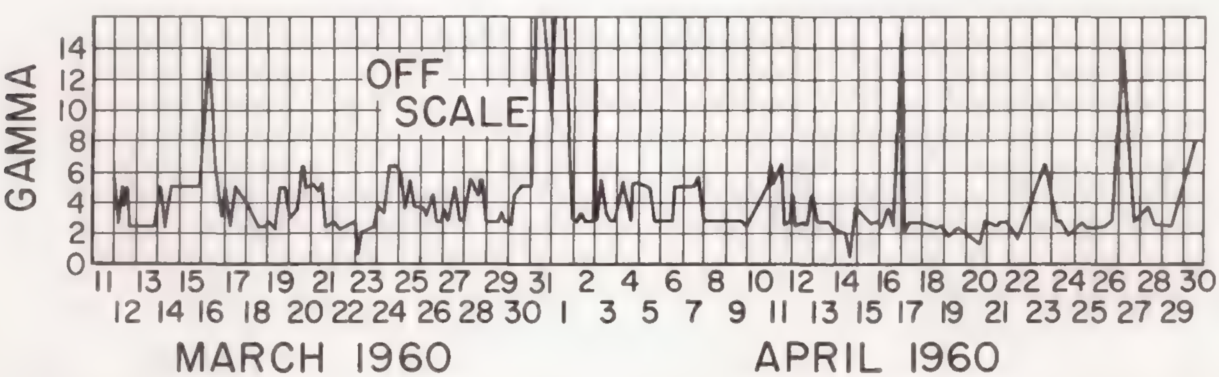

FIGURE 16–19.—Pioneer V magnetometer data. (Points show average value observed during a period of data transmission. From Ref. 3.)

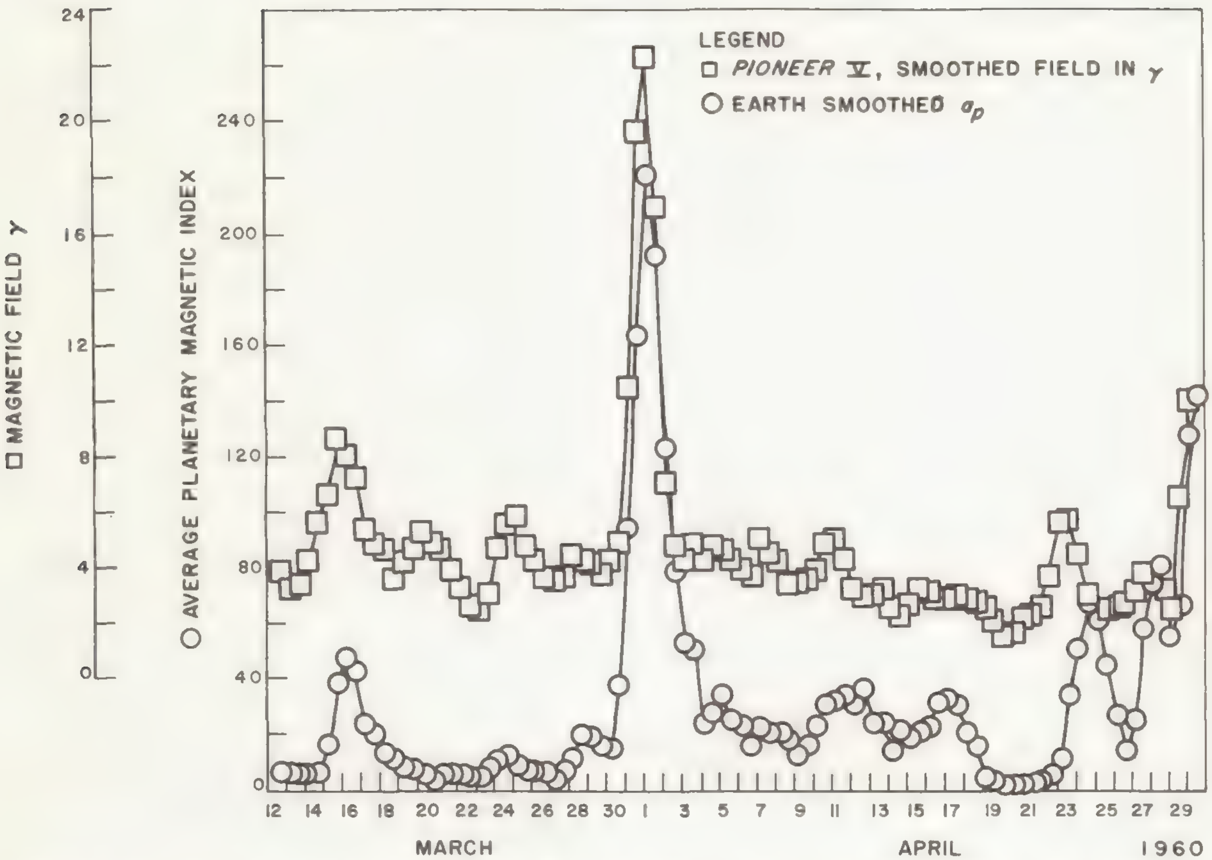

FIGURE 16–20.—Comparison of smoothed Pioneer V magnetic field component and smoothed planetary index a_p. (Planetary index is measure of amount of worldwide fluctuation in geomagnetic field. From Ref. 33.)

On October 7, a typical geomagnetic storm commenced suddenly at 20 hours 25 minutes. On Mariner 2, which was 8,600,000 km nearer to the Sun than the Earth was, everything was quiet between 12 and 15 hours, and the energy spectrum was as shown in the upper part of Figure 16–22. Note that the bulk of the plasma was in the 750-volt level, corresponding to a velocity of 380 km/sec, and that appreciable currents were present also in one lower level and two higher levels. At 15 hours 47 minutes, the nature of the solar-wind spectrum changed abruptly to that shown in the lower part of the Figure. What appears to have happended was that the quiet, slow plasma was overtaken and displaced by a more energetic plasma having a velocity about 20 to 25 percent greater and a density about 6 times as great. The suddenness of the change indicates that the new plasma cloud had a shock front as its forward boundary, as would be expected. In Figure 16–23, we show a time history of the event in greater detail. Note that both the plasma and the magnetic field were very quiet prior to the passage of the shock and very disturbed thereafter. This also is characteristic of a shock. Our measurement of the velocity of this shock is obviously very rough, but if we assume that it is 465 km/sec, corresponding to the level where we saw the most current, then it should have reached the Earth after a delay of 308 minutes. The actual time was 278 minutes, so that the entire picture seems reasonably consistent. If we are lucky enough to see half a dozen such events during the lifetime of Mariner 2, more definite and more detailed conclusions may be forthcoming.

A large number of investigations in recent decades have attempted to find correlations with geomagnetic events and visible occurrences on

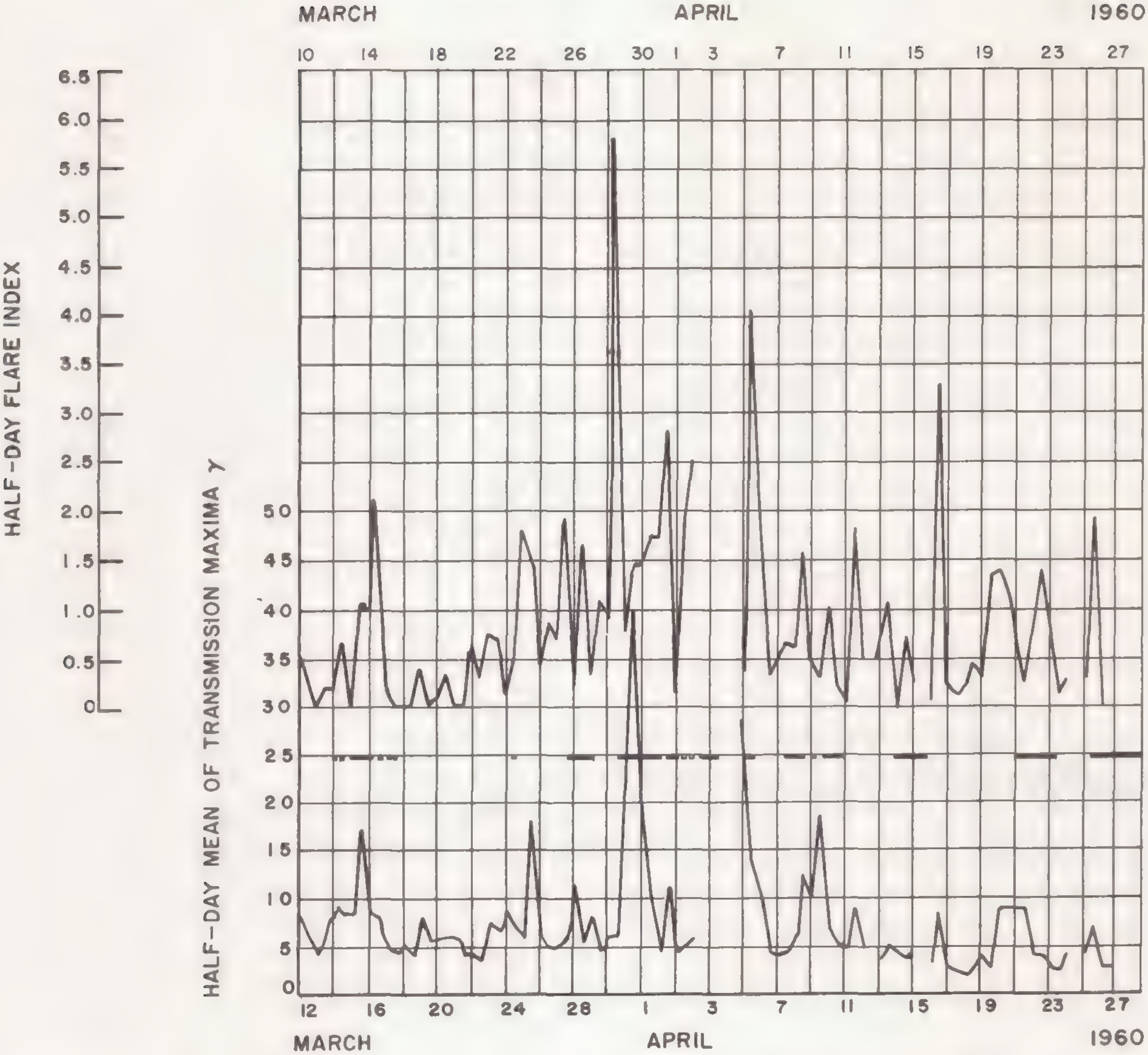

FIGURE 16–21.—Comparison of half-day solar flare index (upper curve) and Pioneer V half-day mean high-field (lower curve). (Horizontal bars are geomagnetic storms. Note two-day shift in solar time scale at top. From Ref. 22.)

the Sun. Two interesting generalizations have emerged from these studies. First, magnetic disturbances of moderate intensity tend to begin gradually and to recur at intervals of approximately 27 days. Second, the more intense disturbances tend to begin suddenly, and hence are called *sudden-commencement storms;* they do not recur periodically but are very highly correlated with the occurrence of solar chromospheric flares.

The statistical distribution of magnetically disturbed and magnetically quiet days is shown in Figure 16–24 (from the work of Chree and Stagg in 1928, Ref. 34); The significance of the 27-day period which stands out so clearly in these data is that it is the synodic period of rotation of the Sun at intermediate latitudes. It would appear that certain restricted regions of the Sun continue emitting streams of plasma for considerable periods of time. These regions were named *M-regions* by J. Bartels (Ref. 35), but they have never been positively identified.

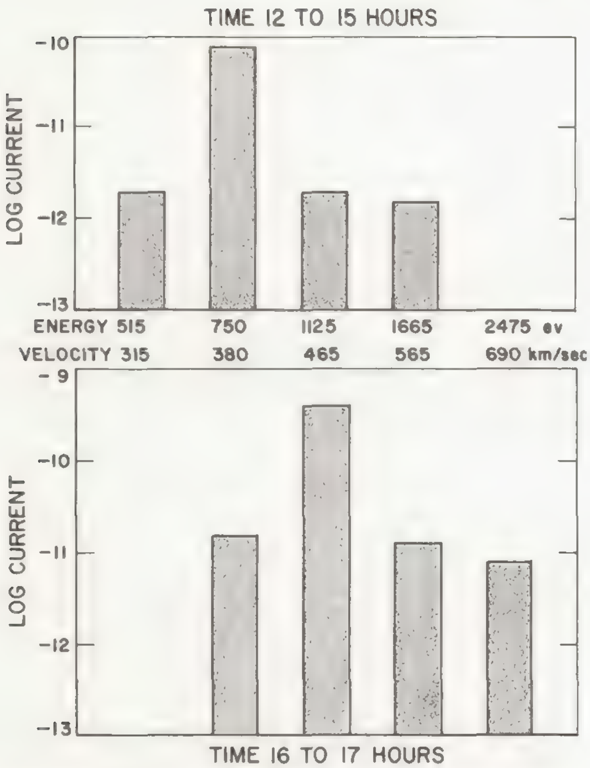

FIGURE 16–22.—Average solar-wind spectra before and after sudden-commencement magnetic storm observed by Mariner 2 at 1547 UT October 7, 1962, showing sudden increase in density and velocity.

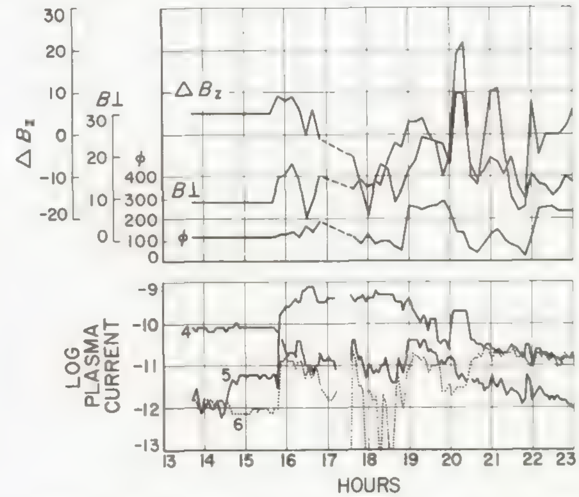

FIGURE 16–23.—Mariner 2 magnetic field and solar-wind data for portion of October 7, 1962. (Magnetometer data are: B_z, radial field component measured from arbitrary zero; $B_\perp$, component perpendicular to radius from Sun; ϕ, orientation of $B_\perp$. Solar plasma data are: collected currents (in amperes) for energy channels 4(750 ev), 5(1125 ev), and 6(1665 ev). Currents were well above threshold in channel 3 before storm and in channel 7 after storm [see Figure 16–22], but these are omitted in order to simplify the Figure.)

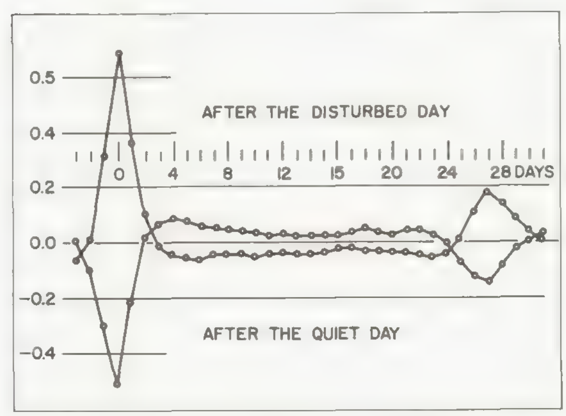

FIGURE 16–24.—Statistical distribution of geomagnetically disturbed and quiet days, showing the marked tendency of magnetic storms to recur after 27 days. (From Ref. 34.)

It will be interesting to see whether any such periodicity can be extracted from the Mariner 2 data on the solar wind.

During the past five years, the number of people and the variety of techniques that are involved in the investigation of solar flares and their terrestrial effects have grown rapidly, and a whole new branch of geophysics has emerged. We can barely skim the surface of this very complex field. Solar flare events vary widely in intensity and exhibit both a large number and a bewildering variety of effects. The time history of some of these effects for a kind of ideal, average, large solar flare is shown in Figure 16–25 (Ref. 36).

At the bottom is shown an intensity-time curve of the visible and ultraviolet light emitted by the flare. The direct effects of these radiations on the Earth are very slight, because only a fractional increase in the total solar radiation of these wavelengths is involved. In the X-ray region, however, where the steady solar output is extremely small, the intensity may increase by a thousandfold or more (Ref. 37). These highly ionizing radiations cause large and abrupt increases in the ionization density in the ionosphere on the sunlit side of the Earth, resulting in short-wave radio fadeouts, sudden increases in the absorption of cosmic radio noise, and other effects. Almost simultaneous with

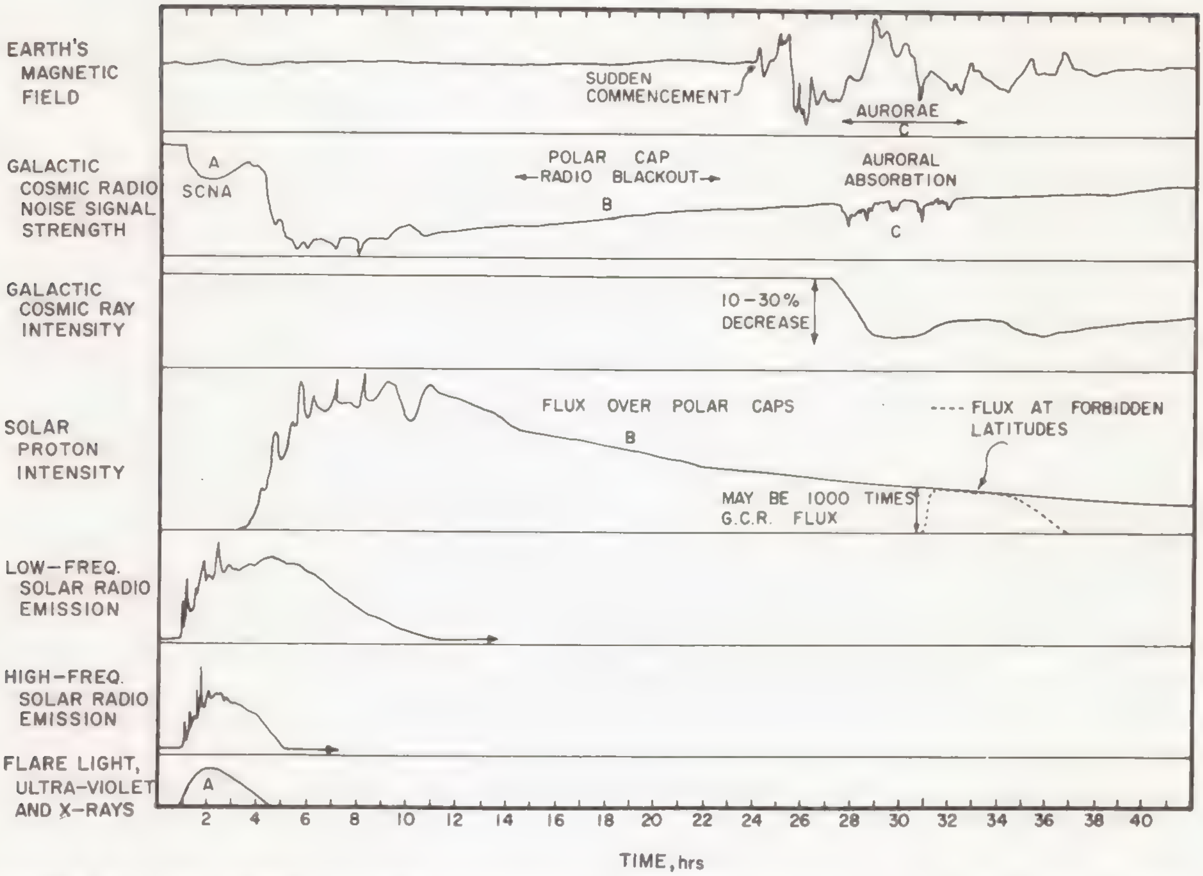

FIGURE 16–25.—Time sequence of most important chromospheric flare effects observable at the Earth. (From Ref. 36.)

the optical emission, there may be a solar radio noise storm, with an enormous enhancement of the radiation from about 10 to 10,000 mc/sec (Refs. 38 and 39). The time variation of the upper frequency end of this radiation more or less follows that of the visible light, but below 500 mc, the emission builds up more slowly and continues for a number of hours. Its center of emission moves steadily higher into the corona. This radiation is known as Type IV radio radiation, and its presence during a flare is strongly correlated with the production of high-energy charged particles in the flare and their subsequent arrival at the Earth (Refs. 40 and 41). The source of all this radio noise is believed to by synchrotron radiation from electrons accelerated to high energies by the magnetic fields in the flare and temporarily trapped by the fields in the corona (Ref. 42).

At the same time that relativistic electrons are generated at the Sun, protons and heavier nuclei are also accelerated to energies exceeding 10 Mev per nucleon. This may always happen, and it is known to happen on some occasions, because of the following observations: At the Earth, following a flare with Type IV radio emission, a rapidly increasing flux of protons is sometimes observed within a few minutes (third curve from bottom). The flux of protons with E $>$ 10 Mev may rise by a factor of 10^4, or occasionally more, above the normal cosmic-ray level (the galactic cosmic rays will be described later) within minutes or a few hours, and it then dies away to the galactic cosmic-ray level during a time of many hours or even days. The solar protons reach the Earth's upper atmosphere in the polar regions and ionize it. This increased ionization partially absorbs radio waves passing through it and thereby decreases the signal strength of the

galactic radio noise in the 30 to 100 Mc/sec range which reaches the Earth's surface (second curve from top).

Finally, 24 to 36 hours after the flare, a burst of plasma reaches the Earth and produces a magnetic storm (top curve). This can be accompanied by auroral displays, and the solar protons may reach the Earth at lower latitudes than was possible earlier before the geomagnetic field was altered by the storm. At approximately the same time, the flux of high-energy galactic cosmic rays which reaches the Earth is reduced, producing what is called a Forbush decrease (third curve from top). These late effects also disappear gradually after many hours or days.

The detailed history of a solar proton event is different for each event. In a single occurrence, the time history of the flux of solar protons is different for each energy particle. However, it is possible to place these events in two categories, one comprising those in which both direct and indirect fluxes are observed and the other, those events in which only indirect fluxes reach the Earth.

The direct flux appears to arrive from a small source, perhaps ±15 deg wide, located near the Sun but not necessarily coincident with it. The protons arrive as if they were released from the Sun within 5 to 10 minutes after the optical flare and then traveled rectilinearly to the Earth. The flux rises to its maximum value in 5 to 20 minutes, the peak in higher-energy particles occurring earlier. The spread in arrival times of particles with different energy depends only upon their velocity; thus, protons of 10 to 20 Mev arrive 40 to 60 minutes after the relativistic ones. The relativistic direct radiation (E>500 Mev) persists for about an hour, while the fluxes of lower energy last for several hours. The intensity of the direct flux can vary during this time, following closely the variations of optical and radio emission from the flare.

Particles occur with energies from above 500 Mev down to 10 or 20 Mev. In a few cases, the differential rigidity spectrum has been measured over this range and is found to lie between p^{-4} and p^{-5}, where p, the "magnetic rigidity," is the ratio of the particle's momentum to its charge.

In contrast to the direct, the indirect radiation arrives isotropically at the Earth. When direct radiation has preceded it, the particles with E>500 Mev can arrived 10 to 15 minutes after the optical flare, while in those cases in which only indirect radiation occurs, the first particles may be delayed by 1 to 3 hours. The low-energy particles are delayed by 30 to 60 minutes beyond their rectilinear travel time in the former case, and do not appear until 4 to 6 hours after the flare when there has been no direct radiation. The intensity of high-energy radiation reaches a peak after an interval 2 to 4 times the delay time, while the lower-energy particles require 6 to 10 times their delay time to reach the maximum intensity.

After the maximum intensity has been reached, the flux begins to decay either immediately or within 1 to 2 hours. Decays proportional to t^{-1} to t^{-2} (t=times in hours) have been reported but Webber (Ref. 43) suggests that after the first few hours, the decay can be described by $N \alpha e^{-t}/t_0$, where N is the flux of particles with energy greater than some value E_0 to t_0 is a constant which depends upon E_0. Decay constants from 2 to 62 hours are reported for E_0=10 Mev, and from 8 to 20 hours for E_0=100 Mev. These variations have been discussed at length by Webber (Ref. 43), and much of the foregoing material has been drawn from his work.

On a few occasions, a second rapid increase of solar proton flux has been observed at the time of the magnetic storm and the Forbush decrease in high-energy galactic cosmic rays. Such an increase in relativistic particles was observed on the Deep River neutron monitor in November 1960 (Ref. 44). A similar increase in the lower-energy flux (9 to 600 Mev protons) was measured by Explorer XII (Ref. 45).

The differential rigidity spectrum of the indirect radiation lies between p^{-6} and p^{-8}; that is, the flux drops off much more rapidly at high energies than does that of the direct radiation. Measurements below 10 Mev have not yet been made, but there is evidence for threshold in the 10 to 100 Mev region, below which are very few

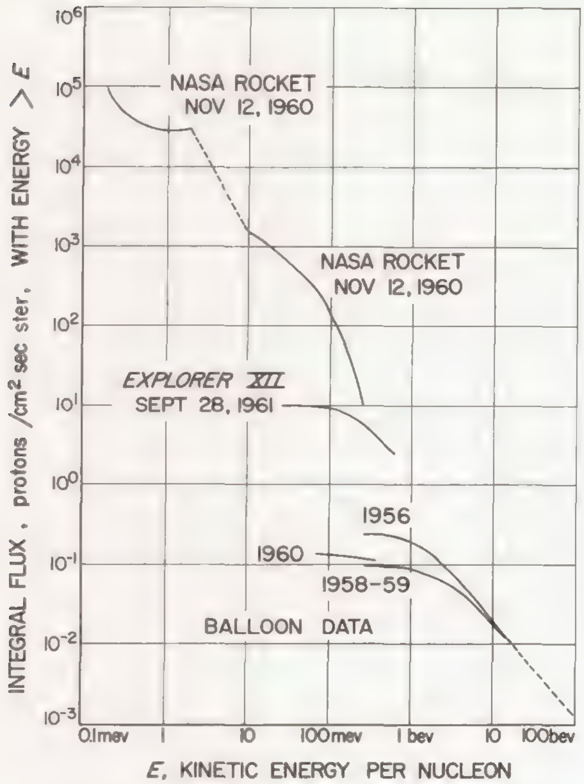

FIGURE 16–26.—Integral energy spectra of solar and galactic cosmic rays. [Top three curves represent solar-flare protons; bottom three curves represent galactic cosmic rays. NASA rocket curves from Ref. 47. Explorer XII curve from Ref. 45. Balloon flight curves from Ref. 55 (1960) and Ref. 52 (1956, 1958–59.)]

particles, since the presence of large numbers of such low-energy protons would produce much more ionization in polar regions than is observed (Ref. 46). The integral flux of protons varies greatly among different events. The largest flux has been estimated for the 23 February 1956 flare, and amounts to about 10^4 protons/cm² sec sterad, with $E>100$ Mev. The majority of other events have produced at least an order of magnitude less.

Figure 16–26 shows a composite of integral energy spectra from various sources. The second and third curves from the top (Refs. 47 and 45) represent two events which were approximately 60 and 100 times less intense than the 1956 event in terms of high-energy proton flux. In the 1960 rocket flight, protons below 10 Mev were actually detected, but the authors suggest that they cannot be regarded as part of the interplanetary solar proton flux.

Although the solar flare particles are predominantly protons, alpha particles and heavier nuclei have been observed also. Ney (Ref. 48) has summarized data obtained in September and November 1960, and finds that the ratio of protons to alphas above the same rigidity varied from 30 to 1, at different times, while the ratio of alphas to C, N, and O nuclei above the same rigidity varied from 42 to 100. The corresponding ratios of abundances in the Sun are 5 and 140 (Ref. 49). In this connection, it should be noted that alphas and heavier nuclei of the same magnetic rigidity have the same velocity, while protons have twice this velocity for the same rigidity. The orbits traversed by individual particles in a magnetic field depend solely upon their rigidity, while the time required for traversal goes inversely as the velocity, of course. It is suggested that the particles are sorted magnetically in passing from the Sun to the Earth.

The electrons, which are presumably accelerated simultaneously with the positive ions, apparently usually do not reach the Earth. Ney (Ref. 48) reports that the flux of electrons in November 1960 was less than 2 percent of the proton flux. Upper limits of 0.25 and 5 percent have been set for other flare events by various observers. However, a small flux of solar electrons (0.015 electrons/cm² sec sterad, with E>150 Mev) has been identified by Meyer and Vogt in July 1961 (Ref. 50).

Neutrons have not been identified, although it has been estimated that their flux does not exceed 5 percent of the proton flux. However, if the protons traverse an appreciable amount of matter between their origin and the Earth, then high-energy neutrons should be present also.

It should be remarked that most flares do not produce high-energy particles which reach the Earth. Approximately 50 solar proton events have been identified since 1956, while there have been hundreds of flares in that time. Although a precise correlation between the characteristics of flares and the arrival of particles cannot be made at present, statistical correlations have

been deduced. The more important of these are:

1. Flares which produce Type IV radio noise are most likely to produce high-energy particles at the Earth. The stronger the noise, the greater the flux of particles observed.
2. Direct radiation has been observed only after flares occurred on the western hemisphere of the Sun. This is the hemisphere that would be connected to the Earth by lines of force on the "garden-hose" model.
3. The time by which the indirect radiation is delayed is greater when the flare has erupted on the eastern hemisphere of the Sun than in the western one.
4. Most, if not all, solar proton events can be ascribed to an observed flare. That is, apparently flares on the invisible side of the Sun very rarely produce high-energy particles which reach the Earth.

At present, no model of the Sun and interplanetary space has been constructed which explains in detail all the observations of solar flares and subsequent events. A rough description that is widely accepted holds that, by an unknown mechanism, the Sun sometimes accelerates particles to high energies at the same time it produces an optical flare. (The mechanism of the optical flare is not understood either.) The electrons spiral rapidly in the solar magnetic field, losing energy to synchrotron radiation, which appears as Type IV radio noise, and perhaps producing the solar X-rays by the bremsstrahlung mechanism. The energetic protons and heavier particles do not lose energy by this means and so escape from the vicinity of the Sun. Their propagation outward from the Sun is determined, for the most part, by the already existing interplanetary magnetic fields. This can be deduced from the time history of solar proton events, and also more directly from the observation that the kinetic-energy density of the solar flare particles is less than or of the order of the energy density of the interplanetary magnetic field. Hence, unlike the plasma, the solar flare particles cannot change the magnetic field a great deal, and so their motion is strongly influenced by the previously existing one. As an example of the

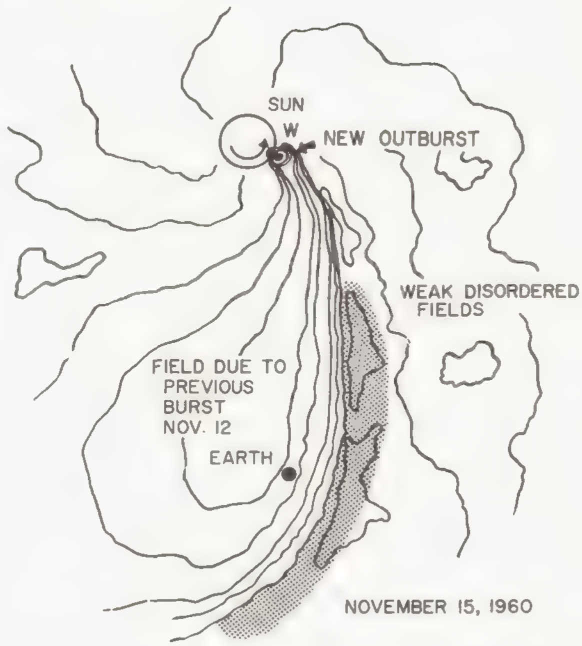

FIGURE 16–27.—Proposed solar magnetic field configuration to explain phenomena observed in connection with the solar flare event of November 15, 1960. (From Ref. 44.)

energy densities, we note that the interplanetary field lies between 3 and 10 gamma much of the time, with energy density between 22 and 250 ev/cm^3. The maximum observed flux of particles with $E>80$ Mev in the November 1960 events was 600 particles/cm^2 sec sterad (Ref. 48), with an energy density of 20 ev/cm^3.

When the Sun is quiet, it is thought that the interplanetary magnetic field is randomly oriented. Flare particles emitted into such a field diffuse outward from the Sun, and if they reach the Earth at all, arrive as indirect, isotropic radiation. The particle flux gradually decreases as the particles diffuse out of this field into interstellar space.

At other times, an oriented field exists between the Sun and Earth. Figure 16–27 shows one conception of such a field (Ref. 44). In this model, a field directed approximately radially from the Sun has been produced by the plasma flowing outward from an active region. In high-energy particles are injected into an existing region of this sort, they travel outward directly along the field lines, spiralling around them with increasing pitch angles, and reach the Earth inside the region as direct radiation.

Because the field is highly ordered, particles injected into it diffuse out rather slowly, maintaining a higher flux inside than out. Similarly, particles diffuse in rather slowly from the region of disordered fields so that, as the region of order expands, the flux of galactic cosmic rays inside it remains lower than the flux outside in the disordered field region. The sequence of events shown in Figure 16-25 is produced when a flare ejects particles into an existing disordered field and, at the same time, expels a plasma cloud which expands slowly out from the Sun, leaving a region of ordered field behind it. The solar protons diffuse through the disordered field and arrive as indirect radiation. The plasma reaches the Earth many hours after the flare, producing a magnetic storm. Then, as the region of ordered field envelops the Earth, the flux of galactic cosmic rays drops, and the solar-flare particle flux increases. The fluxes gradually decay as the plasma cloud expands further.

Most of the evidence which has led us to this picture has been obtained from scientific instruments on the ground or in balloons, although rockets and satellites have recently begun to fill in important details. It will take true interplanetary spacecraft to decide unequivocally among the various models which have been proposed. Our first interplanetary spacecraft, Pioneer V, yielded much important data relevant to the question. One particularly clear event is shown in Figure 16–28 from the records of the University of Chicago cosmic-ray group (Ref. 51).

Pioneer V was 5.2×10^6 km inside the Earth's orbit on March 30, 1960, when a moderately large solar flare occurred at about 1500 hours. A plasma cloud, with its front advancing at an average speed of 2000 km/sec, passed the spacecraft about noon on the following day, producing a Forbush decrease which reached a depth of 28 percent. A slightly smaller decrease was observed on Earth, in company with a geomagnetic storm. At 0845 on April 1, another solar flare occurred, and the protons accelerated by it were able to reach the spacecraft in about an hour, presumably moving along ordered radial field lines.

Recently, the Sun has been exasperatingly quiet, so that no such spectacular event has been seen by Mariner 2, but the analysis of data from several small events is currently proceeding.

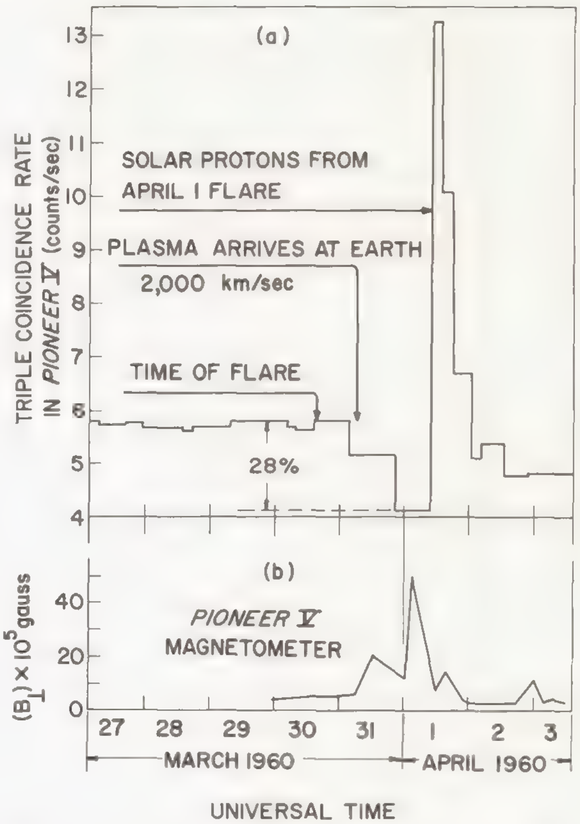

FIGURE 16–28.—Portion of record of Pioneer V triple-coincidence particle detector and magnetometer, showing a Forbush decrease produced by one solar flare and direct solar protons from a following flare. (From Ref. 51.)

COSMIC RADIATION

In addition to the solar wind and the solar-flare particles, there is one other group of charged particles which must be considered in any discussion of the interplanetary medium—the galactic cosmic rays. The history of research on these particles (they are, of course, not "rays") during the past half century is a long and interesting story in itself, but we shall merely summarize the present knowledge about them.

The cosmic radiation is present at all times in the solar system. The high-energy end of its energy spectrum is shown in Figure 16–29 (Ref. 49). Above 10^{11} ev (100 Bev), the flux

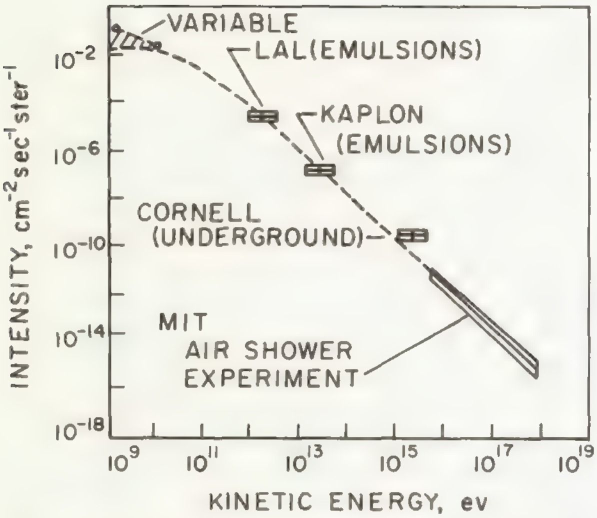

FIGURE 16–29.—Integral energy spectrum of high-energy galactic cosmic radiation. (From Ref. 49.)

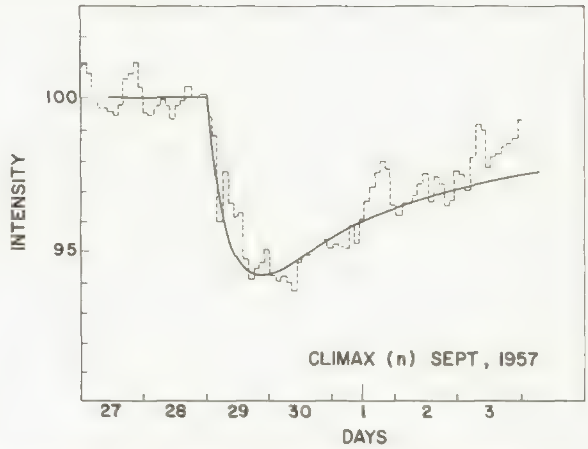

FIGURE 16–30.—Typical Forbush decrease (dashed line) as observed on Climax neutron monitor and theoretical curve adjusted to fit it. (From Ref. 53.)

is very constant and isotropic. The low-energy end, below 100 Bev, is shown in the "balloon data" curves on Figure 16–26 (Ref. 52). Between 300 Mev and 100 Bev, the flux is practically isotropic, except for small deviations during the time of solar disturbances. The energy spectrum in this region is subject to two important variations.

First, there is the Forbush decrease, which occurs following solar disturbances, as has already been described. The elucidation of the exact mechanism of the Forbush decrease is the subject of active theoretical research. Figure 16–30 shows the result of one attempt (Ref. 53) to reproduce the temporal variation of the flux by assuming that the incoming particles execute a random walk through an expanding cloud of magnetically turbulent solar plasma. It should be noted that Forbush decreases can occur without the appearance of any detectable solar protons. The fractional change in flux is generally greater at lower energies than at high.

The second variation in the low-energy cosmic-ray spectrum correlates with the eleven-year cycle of solar activity. The flux has a maximum value at times when the Sun is least active, and a minimum value near the times of maximum activity. The difference between the 1956 and the 1958–59 curves in Figure 16–26 illustrate this fact, and it is shown more clearly

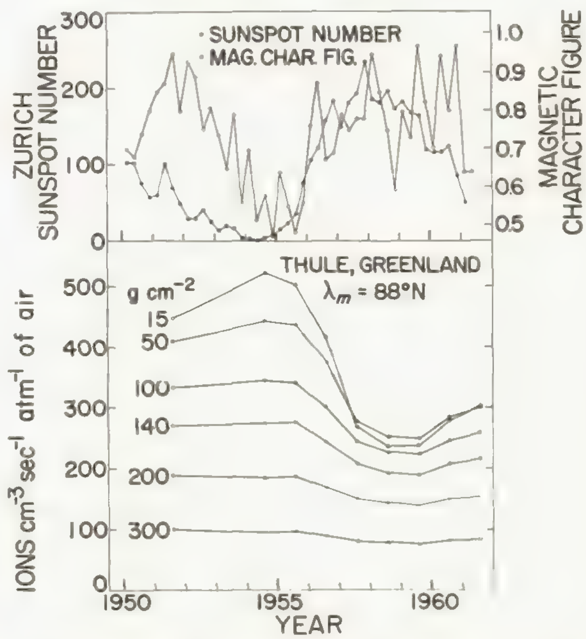

FIGURE 16–31.—Relation of the cosmic-radiation cycle to the sunspot cycle. (Data in top part give quarterly Zurich sunspot number and quarterly planetary magnetic character figure. Data in bottom part give cosmic-ray ionization measured with standard ionization chambers in balloon at selected depths (in g/cm^2) in atmosphere. Note that at large depths, where only high-energy particles penetrate, the modulation disappears. From Ref. 54.)

in Figure 16–31, which compares the rate of ionization produced by cosmic radiation at high altitudes in the polar regions with the sunspot number (Ref. 54). It should be noted that the time of minimum flux does not exactly coincide

with that of maximum solar activity but that the phase of the cosmic-ray variation lags the solar variation by 9 to 12 months.

Very little is known about the spectrum of cosmic-ray particles below 300 Mev, although Vogt (Ref. 55) has detected protons down to 75 Mev, with a differential spectrum that rises with decreasing energy (short curve labeled 1960 in Figure 16–26). Although both Pioneer V and Mariner 2 carried particle counters which were sensitive to such low-energy protons, good energy resolution was not available. Future space probes will cover this very critical region.

The cosmic rays are composed of protons, alpha particles, and heavier nuclei, with the flux of these above a constant rigidity being approximately in the ratio 100:15:2, (Ref. 49). This ratio applies above any arbitrary rigidity (at least up to 10^{13} ev, above which little is known about the composition); that is, the integral fluxes of all nuclear species have the same dependence upon magnetic rigidity, except for a multiplicative constant. The same ratio appears to apply throughout the solar cycle (Ref. 52). The flux of electrons above 100 Mev is a few percent of the proton flux. The relative fluxes of various nuclei approximate the cosmic abundances, except for lithium, beryllium, and boron, which have anomalously large fluxes.

It is generally agreed that the cosmic rays enter the solar system from interstellar space, where the flux is supposed to be uniform and isotropic throughout the nearby portion of the galactic spiral arm in which the Sun is located. This explanation is required for particles with energies above 30 Bev, approximately, because if the Sun produced such particles, they could not arrive at the Earth isotropically. The interplanetary magnetic field is not strong enough to deflect such particles very much. The spectrum of lower-energy particles joins the high-energy spectrum so smoothly that particles of lower energy are thought to have the same source as the higher-energy ones. Also, the fact that there are more cosmic rays when the Sun is quiet than when it is active suggests that solar activity modulates the flux of cosmic rays but that the rays do not originate in the Sun. It should be noted that some of the low-energy cosmic rays could be produced in the Sun if the Sun is able to produce a steady trickle of them.

The motion of galactic cosmic rays within the solar system is controlled by the previously existing magnetic fields, since the particle energy density is much less than the energy density of the interplanetary magnetic field. Forbush decrease modulation models have already been described. The depressed level at times of high solar activity must be produced by the action of magnet fields extending throughout all of the inner solar system or at least surrounding a volume which contains the Earth's orbit. The fields are stronger when the Sun is more active, and the phase lag between solar activity and cosmic ray modulation is explained by the time required for the fields to be established over so large a volume. The correct model for this modulation remains unknown at present, and it is not even known whether the flux decreases gradually as one approaches the Sun from interstellar space, or whether it drops abruptly on some shell surrounding the Sun. The latter might be the case if the barrier to galactic cosmic rays is produced by the interaction of solar plasmas and fields with the magnetic field of the local spiral arm. It is also possible that some low-energy particles in interstellar space are excluded from the solar system even at solar minimum.

Cosmic rays are important to an understanding of cosmic astrophysics if for no other reason than that they are the only thing which reaches us directly from outside the solar system except starlight. Also, their energy density of 1 ev/cm^3 is about equal to the estimated energy density of the local galactic magnetic field, to the energy density of starlight, and to the density of the kinetic energy of turbulent motions of the interstellar gas. Thus, the energy of motion of the cosmic rays appears to be an important fraction of the total energy generated in the stars.

The origin of the rays is not completely understood. Morrison (Ref. 49) supposes that we see the sum of fluxes from many sources, thoroughly mixed in the interstellar magnetic field. The Sun produces particles with energies up to several Bev on occasion, and some of these escape the solar system. Presumably, other stars like the Sun produce energetic particles also,

but accelerators more powerful than the Sun are required to generate the higher-energy cosmic rays. It is possible that the cosmic rays are related to the sources of non-thermal-cosmic radio noise in much the same way that solar-flare particles are related to Type IV radio bursts. Both the Type IV bursts and the cosmic noise are apparently synchrotron radiation from electrons.

CONCLUSION

Terrestrial radiation monitors and balloon-borne instruments have obtained most of the information we have about radiation in space. Among the more important observations by spacecraft so far are the demonstration by Pioneer V that neither the Forbush decrease nor the 11-year modulation are Earth-centered but occur very far beyond the magentosphere (Ref. 56), and the measurements by Explorer XII outside the magnetosphere of the spectrum of solar protons throughout a solar flare event (Ref. 45).

In order to further elucidate the physical processes in the Sun and the interplanetary medium, the following types of measurements should be made using spacecraft:

1. The fluxes of protons and heavier nuclei should be measured during solar flare events near the Earth but outside the magnetosphere, so that the measurements can be extended unambiguously to low-energy particles. Directional data should be obtained. The gap between radiation plasma (10 Kev to 1 Mev for protons) should be explored. It is unknown at present.
2. These data should be correlated with precise measurements of the interplanetary magnetic field and the plasma flux made aboard the spacecraft. It is necessary to be completely outside the magnetosphere to do this.
3. The above measurements should be made simultaneously at different distances from the Earth and to Sun so that the propagation speeds of various phenomena can be measured and the spatial extent of field regions can be estimated.
4. During quiet times, the flux of low-energy particles should be explored to see if the Sun adds a small, steady flux to the galactic cosmic rays. This measurement should be made in different parts of the 11-year solar cycle.
5. The energy spectrum of protons and alpha particles should be measured simultaneously at several points far from the Earth in different parts of the solar cycle. In this way, the variation of the intensity of the galactic radiation with distance from the Sun can be determined. In order to make this measurement, flights covering several astronomical units of radial distance from the Sun may be required.
6. The search for less common types of radiation should be continued. This will include a search for solar neutrons and the measurement of electrons and gamma rays.

Mariner 2 has made a start on some of these measurements. The flux of protons with $E > 10$ Mev is being measured far from the Earth and in correlation with plasma and magnetic field measurements. Variations in the flux have been observed by the Mariner radiation instruments, and these will be studied intensively.

We have not discussed the special categories of radiation found within the magnetosphere. These include the Van Allen radiation and the auroral particles. This region is intimately connected with the interplanetary medium, and most of what we know about the latter has been learned from data obtained inside the Earth's magnetic field. This, however, is another long story and not strictly part of the physics of interplanetary space.

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17. Planetary Astrophysics and the Exploration of the Solar System

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INTRODUCTION

The non-scientist still tends to picture the astronomer as a man who spends his lifetime on a mountain top, his eye glued to his telescope—a REFRACTING telescope. Indeed, during the 18th and much of the 19th centuries, such was a pretty accurate picture of the situation, except for the mountain top part. (Mountains presented too much of a logistics problem in those days.) The non-scientists and some scientists also tend to assume something about the program of the astronomer. They are sure that it must be composed of three or four parts Moon and Planets to one part stars and other things. Again that's not a bad guess for the 18th century, although nothing could be further from the truth today.

During the 19th century, physicists first began to achieve a qualitative understanding of the interactions of radiation and matter. Astronomers were at last being given a tool which seemed to offer hope for some understanding of the enigmatic universe beyond the solar system. By 1907, George Ellery Hale was able to state that (1) "In astronomy the introduction of physical methods has revolutionized the observatory, transforming it from a simple observing station into a laboratory, where the most diverse means are employed in the solution of cosmical problems." Hale proceeded to launch the new science of astrophysics in an all-out assault on the fundamental problems of stellar evolution.

During the ensuing half century, astrophysicists plunged into stellar and galactic problems, never to return to the more mundane affairs of the solar system. Only the Sun received significant attention; but after all, it is a star. In fact, planetary astronomy gradually acquired a bad reputation due to overly enthusiastic Sunday supplement writers and overly ardent amateur astronomers with little training in physics. Hale never intended for this to happen. He wrote that the problems of astronomical evolution could only be considered solved when we understood the formation of a planet like the Earth, that the astrophysicist's work ended only when he began encroaching on the domain of the geologist.

Today we are at a new threshold very like that crossed by Hale. In Hale's time, the wedding was that of astronomy and physics. Today's wedding is that of astrophysics and space vehicles, a wedding which should prove even more prolific than its predecessor. Unfortunately, astrophysics is ill prepared for the wedding, either in temperament or knowledge. Examples of what is needed to make the marriage a success, at least in one part of

the space program, constitute the bulk of this presentation.

VENUS

Man's first successful planetary space probe, Mariner II, is presently on its way to Venus. It will be followed by other Mariners and Voyagers and perhaps, in a decade or so, by man. I say "perhaps" quite advisedly. Venus is apparently extremely inhospitable and could reject man's advances for several decades. Basically we know almost nothing about the planet, which makes it difficult to prophesy. Let's consider the obviously very important problem of atmospheric composition in some detail as an example of our knowledge. The proper design of even the simplest unmanned capsule for entry into the Venus atmosphere depends upon knowledge of composition. Our entire program of scientific study of and eventual manned flight to Venus depends upon such knowledge. Yet only a year ago, it was found that, carbon dioxide, instead of constituting 50 to 90 percent of the atmosphere, makes up perhaps 4 to at most 20 percent of it (2, 3).

Carbon dioxide was first discovered on Venus by Adams and Dunham in 1932 (4) when they identified three near-infrared rotation-vibration bands of $\lambda\lambda$ 7820, 7883, and 8689. Since that time, a number of estimates of the absolute amount of CO_2 have been made, the best known being that of Herzberg (5) who found there to be about 1000 m-atm of the gas above the effective reflecting layer. More recently (3), Spinrad found that 2000 m-atm of CO_2 were required to produce the observed strength of the λ7820 band on an average plate. Since these determinations are made by comparison with laboratory spectra and depend somewhat upon the model atmosphere assumed, the two results are entirely consistent, although not offering the accuracy one would like.

Venus is a planet very like the Earth in size and density. It has at times been called Earth's twin. Therefore, when 1000 m-atm of CO_2 (1/6 Earth atmosphere partial pressure of the gas) were found high in the atmosphere, it was assumed by most that CO_2 must constitute the bulk of the Venus atmosphere. Spinrad (3), however, measured the total pressure from the pressure broadening of the rotational lines and found that the actual total pressures were very high, CO_2 in fact constituting only a few percent of the atmosphere rather than the bulk of it. What, then, makes up the bulk of the Venus atmosphere?

Nitrogen makes up the bulk of the Earth's atmosphere. Unfortunately nitrogen has no sensible absorption features at wavelengths capable of reaching the surface of the Earth. All important bands lie on the short wavelength side of the atmospheric cut off at λ3000. However, in the violet and blue parts of the spectrum, there are emission features due to nitrogen which are found in terrestrial airglow. Kozyrev (6) was the first to identify emission features which he felt could be attributed to N_2 and N_2^+ in the atmosphere of Venus on the dark side of that body. The big problem here is that of contamination by scattered light in the Earth's atmosphere and in the telescope. Newkirk (7) made observations in this country which in part agreed and in part disagreed with those of Kozyrev. An analysis of the results of both Kozyrev and Newkirk by Warner (8) seemed to indicate the definite existence of nitrogen and the possible existence of oxygen on Venus in spite of the fact that the "signal-to-noise ratio" was very poor on the plates of both observers. A repetition of the observations by Weinberg and Newkirk (9), using better equipment, however, gave a completely negative result. Perhaps there was just no aurora during the last mentioned observations. Weinberg and Newkirk noted that visual observations by the BAA (British Astronomical Association) indicated an unusually prominent "ashen light" (a pale glow from the dark side) during Newkirk's first observations which were made near sun-spot maximum and no ashen light at the time of the new work. Observationally, the problem must still be considered wide open, although theoretically one would be hard pressed to find an adequate substitute for nitrogen to make up the bulk of the Venus atmosphere.

What about water vapor? On the basis of observations made during the Moore-Ross balloon flight of 1959, Strong (10) found 19 microns of precipitable water vapor in the atmosphere of Venus above the effective reflecting layer for 1.13-μ radiation. This result is

unfortunately very uncertain, as no measurements of the amount of water vapor above the balloon in the Earth's own atmosphere could be made because of problems with the balloon. The most recent ground-based determination of water vapor on Venus is that of Spinrad (11) who found that the mixing ratio (water vapor divided by total atmosphere) on Venus is less than 10^{-6} by mass, above the effective reflecting layer or, equivalently, less than 7×10^{-3} g/cm^2. This is still a factor of almost four greater than the amount tentatively found by the balloon flight, so there is neither disagreement nor an actual answer to the question of how much water there is on Venus.

The positive detection of oxygen on Venus was announced just a few months ago at the 11th International Astrophysical Colloquium at Liège by the Russian astronomers Prokofiev and Petrova. They found a definite asymmetry in the α band of O_2 that could only be attributed to a doppler-shifted contribution by Venus oxygen. Thus far, Prokofiev and Petrova have made no quantitative estimate of O_2 abundance, stating only that it is small. The real mystery is why this asymmetry doesn't appear on existing Mt. Wilson plates. The Russians were using very high dispersion, 1 Å/mm, on very sharp lines. Also, the phase angle appears to have been somewhat different from that of the Mt. Wilson plates. These small differences must be sufficient to explain the discovery. Perhaps the real mystery is why fewer than two dozen good high-dispersion red and infrared spectrograms of Venus have ever been taken in this country.

Several efforts have been made by various individuals to detect other, perhaps minor, constituents of the Venus atmosphere. Minor species play a major role in the structure of the chemosphere, as well as giving valuable information on major species which may be less readily detected. Thus, Sinton (12) has recently reported detecting a few cm-atm of carbon monoxide. For various reasons formaldehyde has been looked for from time to time. A recent search by Spinrad (11) has confirmed the earlier result of Wildt (13) that 0.3 cm-atm is an upper limit to the formaldehyde abundance in the upper atmosphere of Venus. Spinrad has also confirmed, as was already reasonably certain on theoretical grounds, that there is no major amount of molecular hydrogen present. Kuiper (14) was unsuccessful some years ago in a search for NH_3, CH_4, C_2H_4, C_2H_6, and N_2O.

A number of observers have noted the low albedo of Venus in the violet and near ultraviolet. Heyden, Kiess, and Kiess (15) suggested that this might be due to the presence of nitrogen tetroxide. Spinrad (16) has noted that actually Venus reflects more ultraviolet with respect to the visual than the Moon does, negating any need for the N_2O_4 hypothesis. Kaplan (17) has found that the ultraviolet spectrum of Venus is not coincident with that of N_2O_4 in any event.

The preceding paragraphs present a fairly comprehensive survey of our observational knowledge in one important field, the atmospheric composition of Venus, as an example of the present state of planetary astrophysics. In summary, we know that Venus has a few percent CO_2, probably some N_2—although no one knows how much—a little O_2, a very little CO, maybe some H_2O, and no detectable amount of several other things.

In less detail, what else do we know, or think we know, or guess, about Venus? Perhaps the most significant single discovery of the century concerning Venus has been that of Mayer, McCullough, and Sloanaker (18) who found in 1956 that Venus exhibited an effective brightness temperature near 600° K at a wavelength of 3.15 cm. Attempts to explain this unexpected result have brought forth several entirely new concepts of Venus. The first and most obvious question is whether the high-brightness temperature is thermal or non-thermal. During the past six years, radio astronomers have made significant progress in mapping the microwave spectrum of Venus from a few millimeters to 10 cm, including the variation with planetary phase (19). One non-thermal model proposed by Jones has fit the data reasonably well by assuming that the microwave radiation arises from free-free transitions of electrons in the ionosphere (20, 21). The ionosphere model suffers from the inability to explain the existence of the extremely high

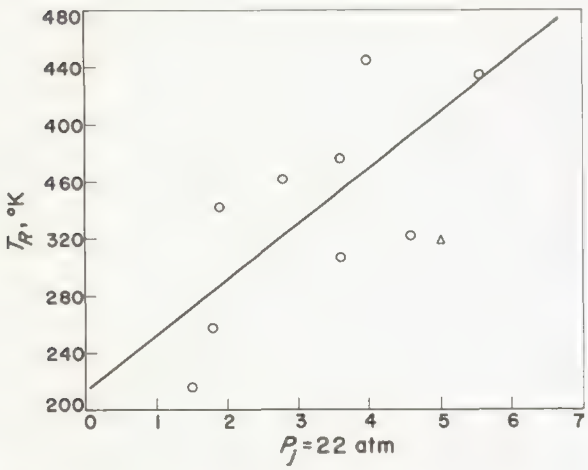

FIGURE 17–1.—The correlation between Venus atmospheric mean temperature and pressures. The straight line is a linear least-squares solution with the triangular point given half-weight. The points do not necessarily refer to a unique geographic location in the Venus atmosphere.

electron density it requires. Yet the two prominent thermal models, Sagan's Greenhouse Model (19) and Öpik's Aeolosphere Model (22), each have their problems too.

The work by Spinrad (3) previously referred to seems to have given the answer to the thermal non-thermal question. Besides measuring CO_2 abundance and total pressure, Spinrad also measured the CO_2 rotational temperature on each plate. Figure 17–1 shows the result. Those plates showing greatest pressures also exhibit the highest temperatures, and further, these pressures and temperatures reach mean values as great as 5½ atm and 440°K. The obvious interpretation is that the Venus cloud cover is somewhat variable in the infrared, radiation coming from deeper in the atmosphere on some days than others. Since the surface conditions must be more extreme than the mean values just quoted, the high surface temperatures must be real, and furthermore they must have very high pressures to go with them.

An important factor in the problem of the Venus atmospheric structure that cannot be ignored is the rotation rate. American radar results (23) strongly suggest that the period of rotation is quite long, perhaps being synchronous with the period of revolution, which is 225 days. If this is the case, one could hardly expect to be able to use the same model for the lower atmosphere on day and night sides. It might seem that very high wind velocities would be required to transport the energy from the day side to the night side to keep the latter at its very high temperature. Mintz (24) has shown however that mean wind velocities of ½ mi/hr or less are sufficient if the surface pressure is 50 atm, while the winds are quite gentle for any of the high-pressure, high-temperature models. Sagan (19) has presented the most complete model of this latter type to date. Very briefly, it has a dark side surface temperature of about 640°K, a bright side surface temperature about 750°K, a surface pressure of 30 atm or more, cloud temperatures of 234°K, dark side cloud pressure of 90 mb, with a subadiabatic temperature gradient to the surface and bright side cloud pressure of 0.6 atm with an adiabatic temperature gradient. The visible cloud deck is at an elevation of about 80 km on the dark side and higher in the bright hemisphere. All of these figures but the cloud temperature have large uncertainties, however, running from perhaps ±10 percent for the dark side surface temperature to perhaps an order of magnitude in the case of the surface pressure. What can we do to improve this unsatisfactory state of knowledge?

First, there are things we can do from the ground. We need hundreds of high-dispersion infrared CO_2 spectra of Venus. We need so many because many variables are involved—phase angle, location on the planet, CO_2 band used, and unfortunately, even time. These spectra are of critical importance because each offers a significant key to atmospheric structure, each giving a simultaneous measurement of temperature, total pressure, and CO_2 partial pressure. We obviously need to make a careful intensive study of O_2 on Venus, the Russian work having shown this to be possible. We should keep a synoptic photographic record of Venus, especially in the near-ultraviolet and in the infrared, where some idea of gross cloud structure can be obtained, for correlation with the spectrographic results and for possible use in meteorological studies. Careful polarimetry can offer additional information, al-

though by itself it rarely offers unique solutions. Careful high-dispersion spectroscopy throughout the spectrum still offers possibilities for discovery, as witness the recent O_2 and CO results. Certainly, radio astronomers should be encouraged to keep up their surveillance of Venus, adding new wavelengths where possible, improving the accuracy of all their data, but especially phase effect information, and looking for possible variations as a function of time.

There should be more balloon astronomy. Potentially, the balloon offers the key to the basic Venus water question: Is there any, and if so, how much? The balloon telescope also offers a factor of about four improvement in linear resolution over what is obtainable from the ground. While this is not enough to be of much significance with respect to Venus (at least, according to our present ideas) such an improvement would be of great help, perhaps mandatory help, in properly identifying the high-resolution pictures of Mars which will be taken with Mariner-type probes to that planet.

An orbiting planetary observatory, an Earth satellite devoted to planetary study, could be of significant importance in studies of all the planets. Such a vehicle offers complete freedom from atmospheric absorptions and turbulence while at the same time allowing something approaching synoptic coverage with large information transmission capability. Its significance would depend in part upon its time scale in relation to that of Voyager class orbiters. For work on the major planets, an OPO should be of use for as much as a decade.

Most significant of all is the true planetary probe. Simple flyby missions of the Mariner class already offer possibilities not presently conceivable while one is limited to the vicinity of the Earth. Consider radio astronomy. Present efforts are limited to the entire disk of the planet and to accuracies of some $\pm 50°K$. at the most favorable frequencies. Within the next few years, microwave radiometers carried by a probe can be expected to give actual thermal profiles, dividing the planetary disk into more than 100 areas, measuring the radiation from each area to $\pm 5°K$. This is extremely significant. Present data are so crude that it is difficult to tell whether a theoretical model atmosphere fits it or not. Almost any model can claim to fit the data. Furthermore, microwave radiometry and spectroscopy in the millimeter region of the spectrum, made quite difficult by terrestrial atmospheric absorption, becomes almost as easy to accomplish as work in the centimeter region.

Present work in the far infrared is limited both by atmospheric absorption and by the comparatively small amount of energy available at those wavelengths (or from another point of view, by the limited sensitivity of our detectors). Even in those comparatively clear parts of the spectrum where we can work, it is necessary to use either very wide pass bands or essentially the entire disk of the planet. Yet, if we are ever to really understand the energy balance of Venus, we must know how solid the cloud cover really is and at what wavelengths the clouds and, for that matter, the unclouded parts of the atmosphere are relatively transparent. Simple multiple-filter infrared radiometers will make a significant start on this problem. Later, a more sophisticated scanning spectrometer or interferometer can carry the ball. In the near infrared, direct photographs will be of considerable significance as the presently experimental infrared television tubes come out of the laboratory and into "field" use.

The atmospheric composition problem will be significantly served by the flight of spectrometers sensitive to the ultraviolet. Abundance information on oxygen and ozone will be one result. Extending the work to Lyman α wavelengths will tell us whether Venus has a hydrogen corona. Nitrogen can best be studied by means of its violet and blue emission lines. A probe must fly by the dark side of the planet so that such auroral and airglow studies can be made free of bright side "contamination." In the far ultraviolet beyond 2000 Å such contamination is no longer a problem, and visually blind detectors will allow daylight airglow spectrometric studies.

At such time as a Venus orbiter becomes feasible, two highly significant spectrometric experiments will be possible, the so-called sunset and twilight experiments. In a sunset experiment, the spectrometer looks directly at the setting Sun through the atmosphere of the

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planet, offering a case of essentially pure absorption and theoretically the easiest case to interpret quantitatively. In a twilight experiment the phase angle, Sun-planet-probe, is 90 deg, and as the probe passes over the terminator, successively lower (or higher) layers of the atmosphere become illuminated, thus allowing some altitude "dissection." Although such experiments are possible in theory on a flyby mission, the single pass and high angular rates of such a mission make the possibility comparatively unattractive.

In many situations, say for use on the Moon or Mars, a landing capsule is not such a fearsomely difficult mission. On Venus it is. The mildest surface conditions most of us are even willing to consider today are 600°K and 5 atm, with 650°K and 10 atm a better bet, and 750°K and 100 atm a possibility. Little has been said about the Venus clouds, but there is a possibility that they are dust, which doesn't help matters any. Not knowing what conditions really are, any early entry capsule must allow for as many extremes as possible. By the time a scientific package has been protected against Venus, there is very little of that package left with which to study Venus. Early entry capsules will almost certainly be just that and no more, with no attempt made to survive the landing. Such attempts, however, may give us direct measurements of the composition and thermodynamic variables of state of the Venus atmosphere attainable in no other way, information that is absolutely necessary if we ever are to land an instrument package, let alone a man, on Venus.

THE OTHER PLANETS

In a few minutes it is hardly possible to discuss the solar system in detail, little as we know. We have concentrated on Venus, since too much planet jumping just becomes confusing. However, a brief sample of the other planets should be given just to prove that Venus isn't an especially intransigent case.

If the slit of a spectrograph is placed perpendicular to the equator of a rapidly rotating planet, such as Jupiter, the spectral lines, of course, will be Doppler-shifted to the red or the blue, depending upon whether the slit is nearer the receding or approaching edge, that is, whether there is a velocity component away from or toward the spectrograph. If the slit is placed parallel to the equator, the lines will be inclined, the amount of displacement being proportional to the radial velocity at each part of the slit. Actually, the situation is a little more complicated than it first appears, since the spectrum actually consists of three kinds of lines: those originating in our own atmosphere, those due to Jupiter's atmosphere, and the solar Fraunhofer lines. If the latter are said to have an inclination of unity, then the Jovian lines should have an inclination of 0.5 and the terrestrial lines an inclination of zero.

Actually, very few plates have ever been taken with a slit parallel to the equator. The inclinations are more difficult to measure than a simple parallel displacement with respect to an iron arc comparison spectrum. Furthermore, the displacements of the Fraunhofer lines are generally used rather than intrinsic Jovian lines because they are much stronger and easier to measure. Last Spring, Spinrad made a high-magnification enlargement of one of the three Jovian plates in the Mt. Wilson Observatory plate files taken with the slit parallel to the equator. The result looked rather peculiar, so Spinrad carefully measured the plate. Then he had several other people do likewise without telling them why. The inclination of the Jovian ammonia lines was only 0.26 (25). Hearing of this strange result, Dr. Guido Münch, professor at the California Institute of Technology and consultant to JPL, immediately loaned his one 200-in. plate of Jupiter to Spinrad and took several others at the first opportunity. The Dominion Astrophysical Observatory in Canada loaned us the one plate in their files. There can be no question of the reality of the anomalous inclination of the Jovian ammonia lines which are shown in Fig. 17–2, although the result is not obvious without actual measurement.

The obvious interpretation of the observed result is that the ammonia is rotating about 6 km/sec more slowly than the bulk of the Jovian atmosphere. That is scarcely palatable. A 6-km/sec "jet stream" might be acceptable, but just ammonia? Actually, the velocity fluctuates with time and perhaps with latitude. A

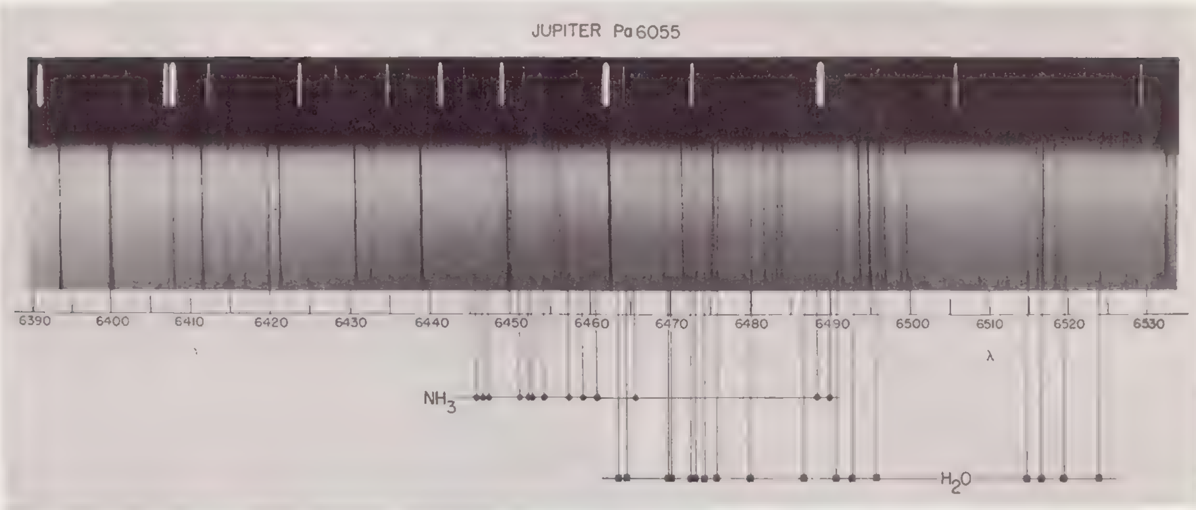

FIGURE 17-2.—A Palomar 200-in. reflector coudé spectrogram of Jupiter taken by Münch with the slit parallel to the equator. Original dispersion 3.3 Å/mm. Most of the unmarked lines are reflected Fraunhofer lines.

large number of plates are needed for empirical study of the problem. Spinrad reports that methane may misbehave somewhat also, although suitable plates for such study are not available. Figure 17-3 is a 200-in. direct photograph of Jupiter. It would certainly be interesting to know what relationship, if any, these anomalous results have with the intricate Jovian cloud structure. All of this may seem a bit remote, but the first unmanned probe will probably head out toward Jupiter in less than a decade, and it would be nice to have at least the preliminary spade work out of the way. Actually, Jupiter presents just as many fascinating problems to us today as does Venus, and probably more. Venus was chosen rather than Jupiter for more detailed comment only because the problems there are more immediate.

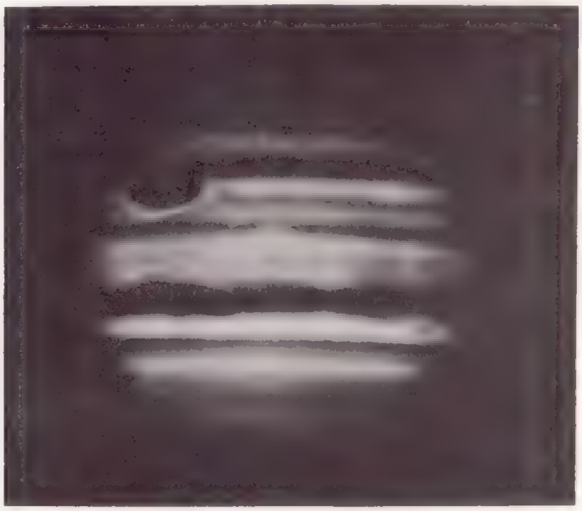

FIGURE 17-3.—Jupiter in blue light. 200-in. photograph, courtesy of Mt. Wilson and Palomar Observatories.

Consider Saturn, the beautiful ringed planet shown in Fig. 17-4. Kuiper (14) has reported the presence of somewhat less than 2.5 m-atm of ammonia on Saturn. Figure 17-5 is a new high-dispersion spectrum of Saturn taken this Summer. It is obviously of high quality, showing a multitude of methane lines, but in a careful search, Spinrad, Münch, and Trafton (26) reported that ammonia was nowhere to be found. Most ammonia will be frozen out in Saturn's atmosphere at all times. Comparatively small temperature changes may be responsible for the "now you see me, now you don't" role played by ammonia. Only additional study can tell.

Even Mars presents its multitude of problems. Some time ago, Kiess, Karrer, and Kiess (27) presented evidence of the possible existence of various oxides of nitrogen on the planet. Several authors (17, 28, 29) have strongly disputed this result, mostly on theoretical grounds. The observational results can be questioned because Kiess, Karrer, and Kiess were using very marginal small aperture equipment in their work. Kiess, Corliss, and Kiess (30) strongly

maintain that the results are nevertheless correct. A problem such as this is extremely important, having strong bearing upon the problems of life on Mars and of manned landings there. The obvious solution is to take new plates with adequate equipment, a project in which Spinrad is now engaged. The fact that an argument can rage for three years, when it is capable of almost trivial solution, is symptomatic of one of the great problems of planetary astrophysics. None of the people who care have ready access to adequate observational equipment.

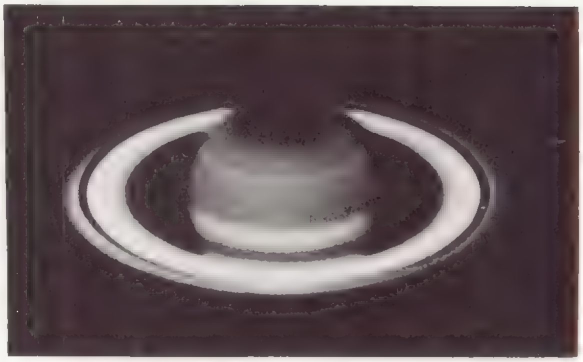

FIGURE 17–4.—Saturn in blue light. 200-in. photograph, courtesy of Mt. Wilson and Palomar Observatories.

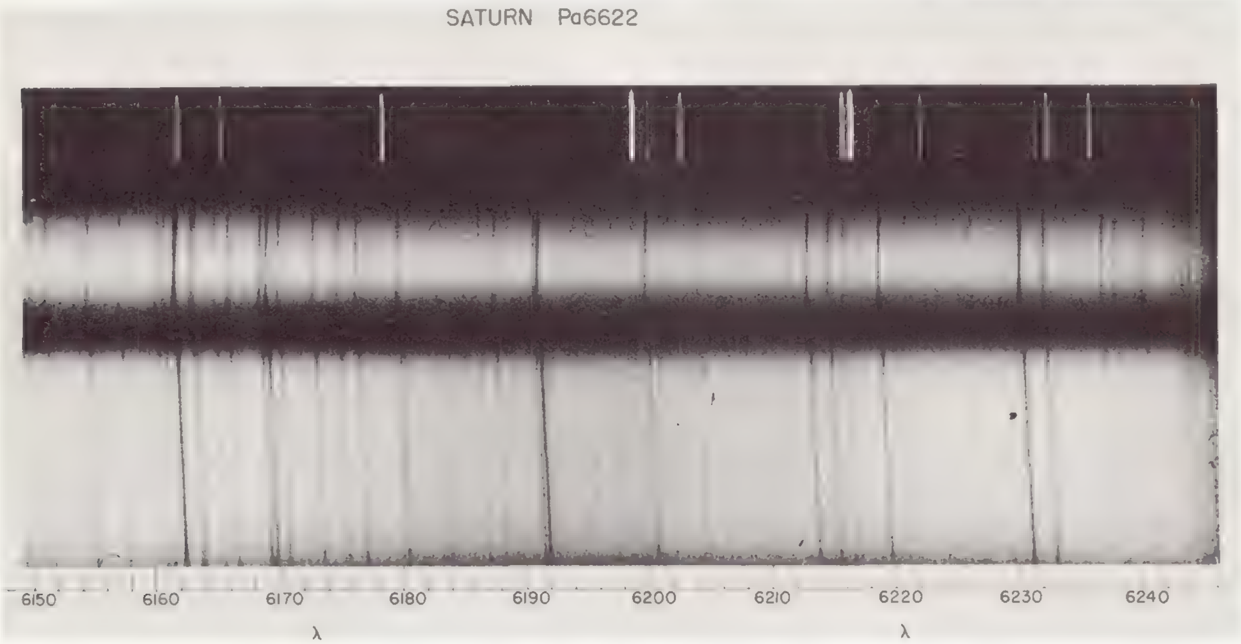

FIGURE 17–5.—A Palomar 200-in. reflector coudé spectrogram of Saturn taken by Münch with the slit parallel to the equator. Original dispersion 3.3 Å/mm. Methane lines can be separated from Fraunhofer lines by the difference in inclination. Note the lack of any methane in the spectrum of the rings at the top.

CONCLUSIONS

Our group at JPL has made some progress during the past two years, because Dr. Bowen, Director of Mt. Wilson and Palomar Observatories, has kindly given us unlimited access to their plate files, because Dr. Münch has worked with us in obtaining new material, because Dr. Herzberg of the Canadian National Research Council has loaned us vital lab spectra, and because Dr. Petrie, Director of the Dominion Astrophysical Observatory in Canada, has been very generous in giving us observing time on their new coudé-spectrograph-equipped 48-in. reflector which was completed just this Summer. All the things discussed here could be discussed only because of the understanding of a few individuals such as these.

Obviously more is needed. You in the universities can help by encouraging young people who wish to study astronomy and, further, by encouraging those who wish to specialize in planetary astronomy. You can help additionally by allowing those individuals who wish

to study the planets to have access to observing equipment. There is no conceivable excuse for using a multi-million dollar space probe to do any job which can be done from the ground.

While discussing Venus, a number of experiments were mentioned which are completely feasible within the present state of space science. Many of them will undoubtedly be carried out, the number depending upon available vehicles and experimenters. There may well be much better, more significant experiments which no one has proposed. We eagerly want new ideas, fresh viewpoints. With the help of the universities, the marriage of space probe and astrophysics will celebrate innumerable joyous anniversaries.

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N63-11101

18. Geological Exploration of the Moon and Planets

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INTRODUCTION

The principal scientific objectives of the exploration of the Moon and terrestrial planets are to understand the nature and history of these bodies. An understanding of the Moon and terrestrial planets is a necessary step toward deciphering the origin and history of the solar system. Knowledge obtained from the exploration of the other planets will also provide clues for answering many fundamental questions concerning the Earth.

At present, most of our knowledge concerning the other planets is based on astronomical observations and inferences. With the ability to conduct scientific measurements on the planets themselves, the disciplines of geology, physics, and chemistry will play the dominant and important role in future extraterrestrial exploration. It is the purpose of this paper to review briefly our present knowledge of the Moon and terrestrial planets, to present specific planetary problems, and to discuss some of the

methods of attacking these problems. Current needs for Earth-based planetology research will also be discussed.

PRESENT KNOWLEDGE OF THE MOON AND TERRESTRIAL PLANETS

General

Existing facts and inferences about the planets, Mars, Venus, Mercury, and the Moon, have evolved slowly during the past 300 years. Advances have not been rapid because unique interpretations of the electromagnetic and dynamical planetary data are usually not possible. Furthermore, most astronomers have concentrated on stellar problems rather than planetary problems. Knowledge of the Moon and terrestrial planets has been obtained by direct visual and photographic observations, by measurements of their electromagnetic phenomena, by inferences made from dynamical data, and by analogy with the Earth and meteorites. It is important to stress the uncertainties in these measurements and, more strongly, in their interpretation.

Moon

Facts and Inferences Derived from Photographs of the Moon. The most detailed knowledge about the surface of the Moon is derived from photographs and visual telescopic observations. Through differences in albedo and topography, many different features can be distinguished on the lunar surface. The most obvious of these are the highlands and maria, which, at full Moon (Figure 18–1), are readily distinguishable from one another by differences in brightness, the highlands having generally 20 percent higher albedo (reflectivity) than the maria. Examined in more detail, it is readily seen that the bright highland areas are covered by a dense irregular pattern of near-circular depressions, termed craters. In contrast, the maria have a much lower crater density, about $\frac{1}{10}$ that of the highlands. Extending outward from many of the craters are rays, thin surficial deposits of high reflectivity. The rays are most strikingly apparent at full Moon, and become almost invisible during other phases. Prominent examples of rayed craters are Copernicus, Tycho, and Kepler (Figure 18–1). The fact that many (old) craters have no rays suggests that these features grow darker with time and disappear, perhaps either through radiation damage or through mixing of surficial debris with micrometeorite bombardment, or both.

In general, two types of maria may be distinguished on the basis of their external shape. Circular maria are best typified by Imbrium (Figure 18–2), Crisium, Nectarus, Humorum and, to a lesser extent, by Mare Serenitatis, while examples of so-called irregular maria are the Maria Tranquillitatis, Foecunditatis, Nubium, and Oceanus Procellarum. Considering the whole surface of the Moon, the number of maria on the visible side is much greater than on its far side, which is over 90 percent highland, judging from the recent Russian photographs (Ref. 1). On the side facing the Earth, for which the only detailed information is available, the maria are always of lower elevation than adjacent parts of the highlands (Ref. 2). Because of their smooth, even appearance, it has been thought that the maria are filled with lavas (Ref. 3), although Gold (Ref. 4) has suggested the filling may be dust and other debris derived from the highlands. Under proper conditions of illumination, however, the maria exhibit a variety of features including low branching ridges and scarps (Figure 18–3), and domes (Figure 18–4), some of which contain small central craters. Long, narrow cracks (rilles) up to 5 km in width and extending for hundreds of kilometers are often found within the walls and regions adjacent to the Maria (Figure 18–3).

Mare Imbrium is probably the best known and most widely studied of the circular maria. In rectified view, this mare is almost perfectly circular in outline (Ref. 5). The western outer margin is defined by two ranges of mountains, the Apennines, Caucasus, and the Alps, which rise 3.5 to 5.5 km above the Imbrian plane (Ref. 6). On the east, the surface of the maria is continuous with Oceanus Procellarum, and on the basis of geologic mapping of the Moon's surface in the general region, Shoemaker (Ref. 1) considers the material filling these two maria to be of the same age. A similar connection through a much narrower opening between the

FIGURE 18–1.—Composite photograph of the full Moon. (North is down. Photograph courtesy Mt. Wilson and Palomar Observatories.)

Apennine and Caucasus Mountains establishes surface continuity between Mare Imbrium and Mare Serenitatis. The large "drowned" crater, Archimedes, along with an accurate string of isolated peaks and short ranges of mountains, occupies the interior of the mare. Another crater, Plato, occurs on the northern rim and is also drowned with material similar in appearance to that covering the area to the south. Extending outward radially from Mare Imbrium for distances as great as 1000 km are a widespread series of linear ridges and furrows, called Imbrian sculpture by Gilbert (Ref. 7). Opinions on the origin of such structure vary. On the hypothesis that Mare Imbrium resulted from impact of a large body, Gilbert inter-

FIGURE 18–2.—Northern portion of the Moon at last quarter showing Mare Imbrium, the rayed crater Copernicus (top, right), the Apennines (top, left), Archimedes (center, left), the Alps (lower, left), with the crater Plato (lower, center). (Photograph courtesy Mt. Wilson and Palomar Observatories.)

preted the troughs as trenches plowed out by low-angle ejecta produced during impact. More recently, Shoemaker (Ref. 1) has revived the opinion that the Imbrian sculpture is the topographic expression of a series of normal faults developed as a result of expansion of the lunar crust during the impact that produced the Imbrian ejecta.

The region of Mare Humorum shown in Figure 18–3 displays interesting evidence of subsidence in both this mare and adjacent parts of Oceanus Procellarum. Mare Humorum is roughly circular in outline and approximately 300 km in radius. The difference in elevation between the mare floor and surrounding areas is approximately 1 km. A series of concentric wrinkle ridges occupies the eastern side of the mare, and the higher terrain still farther to the east is cut by a series of arcuate rilles approximately 300 km in combined length. Rilles on the west side of the mare are much straighter, but one example near the western shore of the mare is slightly curved and shows vertical displacement where it emerges onto the surrounding highlands. This mare is not surrounded by a prominent ridge of debris, as is Mare Imbrium. One of its most striking features is the inward tilting of craters on all but the western margins. The nearly filled crater Letronne in the southern part of Oceanus Procellarum is likewise tilted toward the north, possibly indicating the high terrain between Humorum and Procellarum to be a low anticlinal ridge (the average tilts over the large areas involved are estimated to be ½ deg or less). Other evidence for largescale subsidence in Mare Hu-

FIGURE 18-3.—Mare Humorum (top). Arcuate rilles cut through the crater Hippalus on left (west). The crater Letronne is north (down) of Gassendi, another large partly filled crater with small central peaks on the northern shore of the mare. Gassendi is approximately 110 km in diameter. (Photograph courtesy Mt. Wilson and Palomar Observatories.)

morum and other maria (Nectaris, Imbrium, Crisium, among others) has been discussed by Hartmann and Kuiper (Ref. 5).

Like Mare Humorum and other circular maria as well, except for Crisium, the irregular maria possess no well defined outer rim of mountains or sculpture as does Mare Imbrium. As pointed out by Urey (Ref. 3), another interesting difference between the circular and irregular maria is that in the latter, many partly filled craters are visible in the interiors, whereas vestiges of such structures are almost completely obliterated in the circular examples. This would seem to imply, among other things, substantial filling of the circular mare compared to the irregular ones.

Comparisons between Lunar and Terrestrial Craters and the Origin of Lunar Craters. In the present section, we shall give a brief discussion of attempts at quantitative geologic comparisons between lunar and terrestrial features, dealing in particular with the origin of lunar craters.

Two outstandingly divergent hypotheses have been forwarded for the origin of lunar craters, these being the volcanic and impact hypotheses. Various investigators in the past have attempted to explain lunar craters as either calderas or maars. Gilbert's study (Ref. 7) of this question produced the conclusion that the differences in form and size between lunar craters and terrestrial volcanic craters were so great as to preclude a volcanic origin for the lunar craters. Green and Poldervaart (Ref. 8) answer the objection that lunar craters are of much greater size (on the average approximately two to four times wider and deeper than terrestrial examples) by suggesting that the lower lunar gravity would permit boiling at six times greater depth in the Moon, thereby allowing larger craters to form if explosive activity were to occur. In the absence of quantitative calculations, it is difficult to judge the correctness of such ideas. Baldwin (Ref. 6) has studied quantitatively the

FIGURE 18-4.—Domes (some showing central craters) near Tobias Mayer, small crater which is 30 km in diameter (lower central part). Rhinhold is partly shown in upper right. (Photograph courtesy Mt. Wilson and Palomar Observatories.)

relationship of the diameters, depths, and height of rim above the surrounding plains for lunar craters and shows that data from these features scatter around a curve extrapolated from similar data on craters produced by detonation of high explosives. If such an extrapolation is valid, Baldwin's work suggests that lunar craters can be interpreted as explosion pits. Shoemaker (Ref. 1) questions the correctness of the extrapolation, because of basic differences in the crater mechanics of high-explosive detonation and high-velocity impact.

In an attempt to establish criteria by which results of various crater-forming processes on the Moon might be distinguished, Shoemaker (Ref. 1) has made detailed and extensive studies of the characteristics of terrestrial craters, particularly maars and impact craters.

Terrestrial maars are approximately circular depressions of volcanic origin up to 5 km in diameter and 200 m in depth. Most are partly surrounded by a low, smooth rim of ejecta and fragments of country rock and may have small cinder cones in the center of the main depressions. Maars have funnel-shaped volcanic vents filled with tuff, vent wall rocks, and igneous rocks. They almost always occur in chains or rows. Chains of small craters occur on the Moon at certain places. The most prominent example of this is between Copernicus and Eratosthenes (Figure 18–5), but the situation here is complicated by the proximity to Copernicus, which has a great number of small craters surrounding it that are probably related to the larger crater. The fact that this row of craters merges to the north with a long, low ridge

FIGURE 18–5.—The region between the craters Copernicus (right) and Eratosthenes (left) showing prominent alignment of small craters. The crater Copernicus is about 90 km in diameter. (North is down. Photograph courtesy Mt. Wilson and Palomar Observatories, 200-in. photograph.)

trending across Mare Imbrium and to the south into a rille (the Stadius rille) suggests that the alignment is of internal origin.

Shoemaker's studies of Meteor Crater, Arizona (Ref. 1), show that (at least) terrestrial impact craters in horizontal sedimentary rocks are characterized by several distinctive features: (1) the volume of the rim will, in this case, just fill the depression; (2) debris of the rim is crudely stratified, the sequence of beds being in reverse order of that of the underlying formations; (3) beds of older formations dip gently outward, low in the crater and more steeply near the contact with debris of the rim, and at places are overturned so that the uppermost beds are folded back on themselves; (4) regional jointing controls the shape of the crater, which is somewhat square; (5) the center of the crater (below later lake beds and talus) is occupied by a 200-m-thick lens of breccia, made of material from the underlying formations; (6) deep drilling and shafts have not revealed the existence of a central peak in the center of the crater, although such a feature has been found in the Steinheim basin, which from all evidence appears to be of impact origin also; (7) the outer slopes of the crater are characteristically hummocky.

The problem of distinguishing between a volcanic or impact origin for lunar craters cannot readily be resolved at present using telescopic observations because most of the diagnostic features of both maars or impact craters are too small to be seen. The most important argument that can be used at present for the identification of impact craters on the Moon is the hummocky topography of the rim debris, according to Shoemaker (Ref. 1), and partly on this basis, he ascribes an impact origin to Copernicus. More certain evidence can only come with detailed examination of the structural and petrographic nature of the rocks of particular craters, which, it seems, can only be accomplished by first-hand investigation with unmanned instrumentation or by man himself.

Indirect Observations of the Lunar Surface and Inferences Regarding Detailed Structure. Information about the fine structure of the lunar surface, that is, microtopographic detail below the limit of telescopic resolution (which is about ½ km) has come from interpretation of photometric, polarimetric, infrared, microwave and radio-echo observations. A point of major importance to be remembered here is that such observations often refer to relatively large areas of lunar surface or, in the case of long wavelength data, to the entire visible disk. The information thus derived represents averages over large areas, which may have little or nothing to do with the properties *at a particular point* on the Moon's surface.

The Moon has some extraordinary photometric properties that must depend on the detailed structure of its surface. At full Moon, the distribution of brightness over the surface of the disk is nearly uniform in contrast to ordinary diffusing spheres which appear brighter near the center when illuminated by a distant light source. The maria and highland regions have nearly the same photometric properties, both being characterized by a maximum apparent brightness at zero phase angle, with sharp changes in brightness before and after full Moon. Models of the lunar surface most satisfactorily explaining these results have the surface covered by deep holes with vertical walls and sharp edges. This microstructure (on some scale greater than the wavelength of light) is such as to give a very strong maximum of reflection in the backward direction. The lunar surface is characterized by innumerable areas of different brightness. This property (along with topography) has been of considerable value in mapping stratigraphic units on the Moon's surface (Ref. 1).

Polarization of moonlight as a function of phase angle gives information on the very fine structure of the surface (Refs. 1 and 9). Observed mean lunar polarization curves giving the proportion of polarized light as a function of phase angle show two distinctive features: (1) for small phase angles, a greater portion of light reflected from the surface vibrates in the plane of vision than in a plane perpendicular to the plane of vision (negative polarization), and (2) at phase angles of 28 deg, the polarization becomes positive and reaches a maximum at a phase angle of about 100 deg. Maximum polarization is attained on the dark regions and minimum on the bright regions, and the polar-

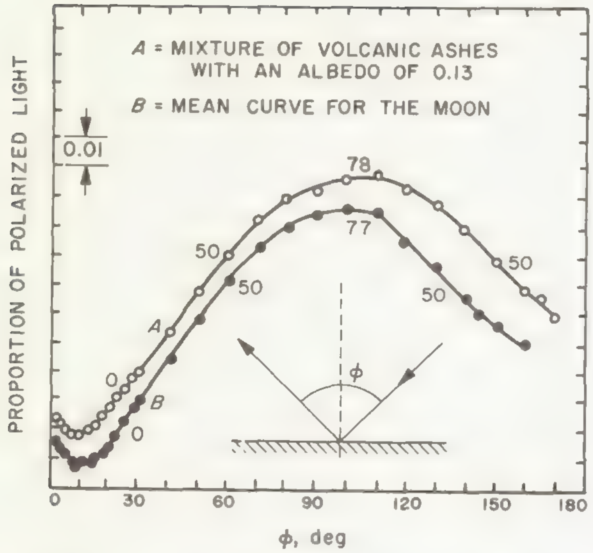

FIGURE 18–6.—Polarization of light reflected from the Moon. (Curve A is mixture volcanic ashes with albedo of 0.13; curve B is mean curve for the Moon. Numbers are proportion of polarized light × 10^2.)

ization varies considerably more on the bright areas than in different places on the maria. The average polarization curve of the Moon is reasonably matched by mixtures of volcanic ashes (alkali-basalt composition) from eruptions of Vesuvius; that is, by a powdered, opaque substance (Figure 18–6). Such powder must stick even to the steepest lunar slopes, and, in view of the photometric data, to the walls of the cavities covering the surface as well, since the polarization curve obtained from slopes and flat areas is the same and is very different from that obtained with bare igneous rocks, whose zero of polarization is at a smaller phase angle (around 10 deg).

Observations of the reflection of radiowaves from the Moon's surface yield information on the average structures of the surface with dimensions of the order of the wavelengths of the waves involved. Studies reported by Evans (Ref. 1) carried out in the wavelength range 0.1 to 3 m indicate that the surface of the Moon is smooth and undulating, with average slopes of about 6 deg, and that on the average about 10 percent of the surface is covered with small objects which are well below the limit of telescopic resolutoin. About 50 percent of the echo power arises as the result of reflections from a region at the center of the visible disk with a radius of 1/10 that of the Moon. From consideration of the echo power as a function of the inclination of the surface to the line of sight, it has been deduced that most of the power is reflected from regions which are nearly perpendicular to the incident ray paths. A study by Daniels (Ref. 10) at 0.68 m has indicated that the rms slope of the small-scale structure of the Moon will have a value somewhere between 8 and 12 deg.

Temperature measurements of the Moon made during eclipses in both the infrared and microwave regions of the spectrum have yielded information about the thermal properties of the near-surface material. Jaeger (Ref. 11) has developed a theory attempting to reconcile all the data into a consistent picture. On the basis of a theory assuming thermal properties to be independent of temperature, the eclipse observations indicate a surface with so-called thermal inertia $[(K\rho C)^{-1/2}$, K being conductivity, ρ density, and C specific heat at constant pressure$]$ of the order of 1000, which may be interpreted as representative of finely divided granular material in vacuum, or at least a thin layer of this material a few millimeters thick overlying a better conductor (equivalent to pumice or loose volcanic gravel). The theory definitely rules out any large part of the surface being covered by pumice or bare rock. This

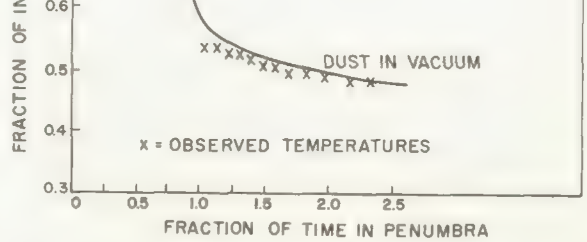

FIGURE 18–7.—Change of temperature during a lunar eclipse. (Solid curves based on calculations by Jaeger, 1953. Crosses derived from measured temperatures (after Pettit, 1940).)

can be seen from Figure 18–7, which shows measured temperatures during an eclipse (crosses), as obtained by Pettit (Ref. 12), together with the theoretical curves of Jaeger for homogeneous rock, pumice, and dust. Assuming a "midnight" surface temperature of approximately 120°K, Sinton (Ref. 1) has calculated that a surface with $(K\rho C)^{-1/2}$ of the order of 500 is required to explain the lunation temperature variation. This discrepancy could easily be removed, it seems, by lowering the "midnight" surface temperature. In fact, recent measurements of nighttime lunar temperatures by Murray and Wildey (Ref. 13) show the surface temperature to be below 105°K. Examination of Sinton's theoretical curves (Ref. 1) shows that a midnight temperature of about 98°K would be sufficient to raise the lunation thermal inertia the required amount to agree with eclipse calculations.

Microwave and millimeter-wave temperature observations as reported by Sinton (Ref. 1) are well represented by an equation of the form

$$T = To' + T_1' \; cos \; (\frac{2\pi t}{P} - \psi)$$

where T'_0 is found to vary between roughly 180 and 315'° K, T_1' is between 5 to 50° K, and the phase angle ψ is 40 to 45 deg. P is the period of lunation. The smaller amplitude of these thermal oscillations and the large phase angle suggest that the radiation giving rise to these temperatures is arising beneath the surface of the Moon. Using either the variation in amplitude or phase lag of the thermal wave with depth, the mass absorption coefficient of the Moon's near-surface material can be calculated. Sinton (Ref. 1) has measured the mass absorption coefficients for some terrestrial materials at a wavelength of 1.5 mm (no values given in the paper quoted) and finds that the observed coefficient, which falls between 0.1 and 0.083 g^{-1} cm^2, is closest to that of basalt. Stone meteorites have coefficients near 9 g^{-1} cm^2, while tektites have coefficients near 2 g^{-1} cm^2.

Observations of emission at these longer wavelengths are usually taken as averages over the whole disk of the Moon. Therefore, such conclusions as can be drawn from the data may have, as we have said, little or nothing to do with the near-surface characteristics of the Moon at specific points

The observations just summarized point to an "average" model of the Moon's surface which is extremely rough on some scale below the limit of telescopic resolution, probably on a scale between 10 cm and 3 m. The walls of cavities and surface irregularities present are covered by a thin layer of finely divided opaque material, which may overlie other debris such as pumiceous gravel.

Lunar Surface Problems. It has not been possible in this brief review to cover many significant features (of the surficial structure and stratigraphy) of the side of the Moon visible to us from Earth. What we have tried to indicate, however, is that extended study of the surficial structure (mainly topography) of the lunar surface has given some indication of the processes that have gone into shaping the surface as we now see it, and from this there has emerged a rough idea of lunar stratigraphy and history. Furthermore, telescopic work using special instrumentation has furnished some information on details of the very uppermost surface structure of the Moon that are of smaller size than the limit of telescopic resolution. It is obvious that an understanding of the nature and history of the Moon can come only from further thorough *in situ* investigation of many problems. Some of the most important of these are: (1) absolute and relative ages of lunar surface features and stratigraphic units, (2) chemical composition of the Moon, (3) variation in rock types (textures, mineralogy) over the surfaces, differences between highlands and maria, (4) existence of lunar cruist with high potassium, thorium, and uranium content, (5) the structure of such mountain ranges as the Apennines, Alps, Carpathians, Caucasus, (6) structure and stratigraphy of the highlands and maria, (7) differences between circular and irregular maria, and age relations between all such features, (8) nature of contacts between maria and adjacent highlands, whether depositional or fault (through subsidence), (9) significance of walled plains such as Plato and Archimedes, (10) the nature and

significance of domes, rilles, and wrinkle ridges, (11) the radiation damage of materials on the surface, (12) lunar erosion and debris transportation mechanisms, and the rates of detritus transport from place to place, (13) heat flux from the interior as a function of position over the surface, and (14) variations of surface temperature throughout a lunation over the surface.

Interior of the Moon. The mass of the Moon is 7.3×10^{25}g and its mean radius is 1738 km. The mean density of the Moon, 3.34 g/cm^3, has led to the widespread belief that the Moon is composed of ferromagnesian silicate materials such as are believed to compose the upper mantle of the Earth. Since the maximum pressure in the interior of the Moon is only 46,000 bars, a pressure which is reached at a depth of only 150 km within the Earth, most silicate phase transitions, except possibly the basalt-eclogite transition, are ruled out. Ignorance of the internal density distribution of the Moon has led to wide speculation concerning its internal structure.

From observations of the Moon's libration in longitude and its orbital characteristics, values for the ratios $\alpha=(C-B)/A$, $\beta=(C-A)/B$, and $\gamma=(B-A)/C$ can be obtained, where C is the moment of inertia about the axis of rotation, A about the axis pointing toward the Earth, and B about a third orthogonal axis. These ratios are far greater than those calculated for a homogeneous Moon in hydrostatic equilibrium and imply considerable strength in the lunar interior.

Urey, Elsasser, and Rochester (Ref. 14) point out that the irregular shape of the Moon can be explained by assuming that its density varies with respect to latitude, longitude, and to radius and that great strength is not required in the deep lunar interior. However, the outer part of the Moon must have considerable strength in order to explain certain surface irregularities.

Thermal calculations for lunar models which assume a uniform distribution of radioactivity in the same concentration as in chondritic meteorites (Refs. 15 and 16) indicate that a large part of the lunar interior would be molten (Figure 18–8). It is thus difficult to reconcile data on the Figure of the Moon with a homogeneous Moon of chondritic radioactivity. This discrepancy suggests that the total radioactivity of the Moon is less than that of chondritic meteorites or that the Moon is a differentiated body with the radioactivity concentrated near the surface (Ref. 15).

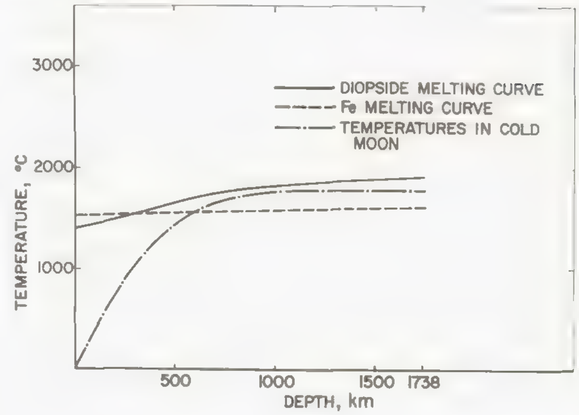

FIGURE 18–8.—The variation of temperature as a function of depth in a model Moon having a uniform distribution of chondritic radioactivity and assuming an initial temperature of 0° C. (Taken from MacDonald, 1962.)

A rough measure of the density distribution or homogeneity of the Moon can be obtained from the ratio of its principal moment of inertia to the product of its mass times the square of its radius. This ratio is formed by dividing β into $(C-A)/Ma^2$, which is obtained from observation of the mean motions of the perigee and node of the Moon's orbit and the main ellipticity term in the Earth's gravitational potential (Refs. 17 and 18). For a homogeneous Moon, this ratio should be 0.4; the observed value is 0.56 and suggests at first glance that the interior of the Moon is less dense than its outer portions. However, Jeffreys (Ref. 18) and MacDonald (Ref. 15) point out that the probable error in the observations is sufficiently large so that this discrepancy is probably not significant.

The question of whether the Moon possesses a magnetic field is still unsettled. In September 1959, the Soviet rocket which crashed on the Moon contained a magnetometer and indicated no evidence of a lunar magnetic field down to the instrument threshold of 6×10^{-4} gauss (Ref. 19). Neugebauer (Ref. 20) has suggested that the Soviet observations are not conclusive.

Further measurements of a possible lunar magnetic field would certainly shed light on the nature of the lunar interior as well as provide clues to the origin of the magnetic field of the Earth.

Topographic and geologic features associated with earthquake belts are not significantly present on the Moon, but the mechanism of lunar seismic energy release may be entirely different from that on Earth. Fairly extensive lunar seismic activity is predicted by the thermal calculations of MacDonald (Ref. 21) and Kopal (Ref. 16). A knowledge of whether moonquakes are localized in belts or are random in location, their correlation with any lunar topographic features, and their depth of focus is necessary for understanding the thermal and tectonic history of the Moon.

Venus

Present Knowledge and Theories of Venus. Our knowledge of the solid body of the planet Venus is exceedingly meager. Fundamental planetary constants are far less certain on Venus than on other planets. Yet, Venus is perhaps one of the most intriguing of the planets because of its resemblance to the Earth in size and density and because conditions may have changed considerably on Venus during the history of the planet.

Telescopic and photographic observations of Venus reveal the absence of sharp features on the planet. Rather indistinct features have been recorded, but they generally lack reproducibility in position and shape in sequential observations. These and other optical data indicate that the lithosphere of Venus is persistently obscured by a dense atmosphere. The high visible albedo of 0.6 to 0.8 is caused by the atmosphere. Ultraviolet photograph of Venus show more distinct markings than photographs taken at visible wavelengths. Figure 18–9 shows three ultraviolet photographs of Venus taken by Ross. Broad bands perpendicular to the terminator are prominent in these photographs. "Polar" caps, bright areas near the cusps of the crescent which vary both in brightness and location, have been recorded in a number of observations. Occasional dark spots observed on the disk have been interpreted by some astronomers as the surface of Venus exposed through breaks in the clouds. The disk is yellowish, apparently the result of Rayleigh scattering (Ref. 22). Figure 18–10 shows Venus in blue light.

Two uncertain factors of critical importance to the study of Venus are its rotation period and the orientation of its axis of rotation. Recent radar measurements of Venus (Ref. 23 and 24) are tentatively interpreted as indicating that the axis of rotation is perpendicular to the ecliptic and that the rotation period is about 225 days. The rotation and orbital periods would thus be similar, and the same face of Venus always faces the Sun. A long rotation period ($>$ 170 days) is calculated by Sagan (Ref. 22) on the basis of surface pressures and the apparent change in brightness temperature with phase. On the other hand, Soviet scientists report that their recent radar data indicate a rotational period of 9 to 11 days (Ref. 25).

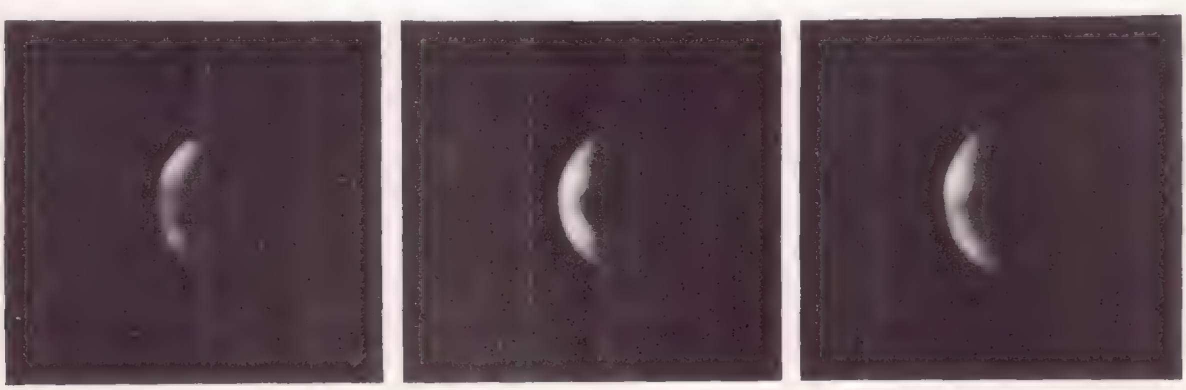

FIGURE 18–9.—Venus in ultraviolet light. (60-inch photographs by F. E. Ross, 1928, on June 24, 26, and 30, 1929. Courtesy of R. S. Richardson.)

FIGURE 18–10.—Venus in blue light. (Photograph from 200-inch reflector, Mt. Wilson and Palomar Observatories. Note lack of irregularities in terminator and absence of other features.)

The dimensions of Venus are uncertain because the depth of its atmosphere is not known. Estimates of the density of Venus, therefore, have a wide dispersion, from 4.8 to 5.5 g/cm^3. Measurements of planetary oblateness are also of dubious value. If Venus has a synchronous rotation, a tidal bulge in the direction of the Sun is probable. Models of internal structure are impossible to construct because nothing is known of Venus' shape or moments of inertia, and Venus has no moons from which its mass can be accurately determined. The current value for the mass of Venus was calculated from perturbations on the orbit of the asteroid, Eros (Ref. 26). The orbital eccentricity of Venus is the lowest in the solar system; seasonal variations on Venus should be minimal.

Figure 18–11 shows brightness temperatures measured near inferior conjunction as a function of wavelength. Emission at progressively shorter wavelengths indicates lower temperatures. Most authorities believe that the surface of Venus is the source of the microwave radiation (Ref. 27), whereas shorter wavelength emission is derived from atmospheric levels. It is possible, however, that the microwave flux may be emitted from an ionized layer in the upper atmosphere or may be a composite of radiation from several levels. The actual surface temperature on Venus may exceed the equivalent black-body temperatures shown in Figure 18–11 because emissivity is not likely to be unity. Victor and Stevens (Ref. 28) measured a reflectivity at 12.5 cm of 0.10 to 0.15 deg; this indicates that the emissivity at that wavelength is around 0.85 to 0.9.

Recently radar measurements indicate a change in brightness temperature as a function of phase angle. Drake (Ref. 29) and Mayer et al (Ref. 30) have estimated 78° K and 146° K, respectively, as the temperature difference of Venus at inferior and superior conjunctions. If Venus has a synchronous rotation, the temperature of the dark side is but 80 to 150° K cooler than that of the illuminated side, assuming the microwave radiation comes from the surface of Venus. Heating of the dark side, therefore, must be by convection and, to a lesser extent, by conduction. This would suggest rather severe atmospheric circulation which should profoundly influence the physical character of the surface of Venus. Calculations by Mintz (Ref. 31) indicate that given synchronous rotation of Venus, strong winds will occur only if the surface atmospheric pressure is small. Mintz suggests that the source of observed microwave radiation may be electrical fields generated in sandstorms produced by the strong winds. If, however, surface pressure is of the order of 50 atm and the temperature is high, the observed variations of the planet's atmospheric heat balance with phase can be accounted for by wind velocities across the terminator of 0.5 mph or less.

Spectroscopic measurements indicate that the water content of the Venus atmosphere is very small to nil. The high CO_2 abundance in the atmosphere is further evidence that water on the surface is probably absent. Surface water would act as a catalyst for reaction of silicates with CO_2 to form carbonates and SiO_2. The CO_2 content of the atmosphere should more nearly resemble that of the Earth's atmosphere if surface water exists on Venus (Ref. 3). Further, if the surface temperature is 600° K,

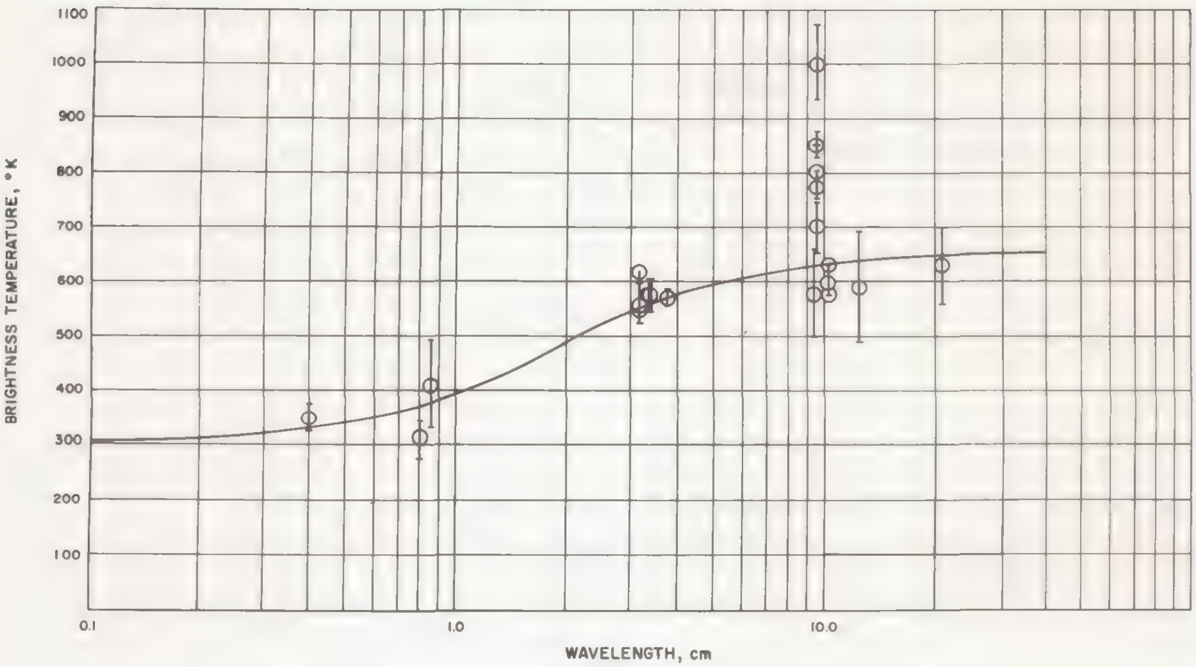

FIGURE 18–11.—Microwave temperatures of Venus obtained near inferior conjunction. (Length of vertical bars indicates uncertainty. From Victor, et al.)

a total atmospheric pressure of 100 bars is required for H_2O to be in the liquid field. This pressure is within the possible range of surface pressure estimated in various ways (Ref. 22). Other investigators have proposed that an ocean blankets the planet's surface; the CO_2-silicate reaction, thus, could not occur. Recent radar data (Ref. 23) indicate a surface roughness on a scale of centimeters comparable to that of the Moon, and the existence of a Venusian ocean, therefore, is improbable. Pettengill et al. (Ref. 24) report that their data indicate a dielectric constant and conductivity in Venus similar to those of rock materials on Earth.

The similarity of mass and density of Venus and the Earth suggests that the two planets have had broadly similar evolutions. By analogy with the probable density distribution of the Earth, Venus contains a core whose radius approximates half the radius of the planet. This inference is supported by Urey's (Ref. 3) calculation that Venus contains about 45 percent (by weight) iron-nickel phase based on the assumption that the mean density of the planet (4.8 g/cc) is produced by silicates (ρ=3.3 g/cc) and metal phase (ρ=7.2 g/cc). The possible slow rate of rotation of Venus would suggest that the magnetic field of Venus may be of much lower intensity than that of the Earth, since the self-exciting dynamo effect would not be similar to that postulated for the Earth. Conversely, Houtgast (Ref. 32) suggested that the field of Venus may exceed that of the Earth from analysis of the decrease of the Earth's field at inferior conjunction over a 44-year interval. He interpreted the data as being caused by deviations of solar charged particles away from the Earth by the stronger Venusian field at the closest approach of that planet to the Earth.

The internal thermal regime of Venus is obviously unknown, but if a surface temperature of 600°K has existed on the planet for some length of time, the flux of heat from the interior has been affected in an important way. MacDonald (Ref. 33) has calculated that temperatures at a depth of 200 km in Venus are about 200°C higher than at the same depth in the Earth if Venus has a chondritic abundance of the radioactive elements. These temperatures should exceed the melting points of silicates at this depth, and magmas may be

formed to a greater degree in Venus than on the Earth. MacDonald further suggests that if Venus originally had an angular velocity equal to that of the major planets, the existing rotation rate can be accounted for by anelastic dissipation of rotational energy in the zone where silicate fusion is approached. It should be emphasized that these extrapolations serve only to point out the geologic consequences of a combination of fundamental assumptions and a few planetary measurements whose interpretations are most uncertain.

The existence of a thick atmosphere on Venus suggests that initial chemical differentiation of Venus was similar to that of the Earth. It is likely that Venus has a core and a silicate mantle similar to the Earth. A principal question is whether Venus possesses a crust similar to that on Earth.

The probability of melting in Venus suggests that volcanism has occurred and that constructive land forms have been so produced. The complexity of a Venusian crust is probably a function of the kinds and intensities of erosive and depositional mechanisms operative. If liquid water is currently absent from the surface of Venus, the present relief would be a function of the rate of wind erosion versus rates of crustal deformation and volcanism. If the atmospheric circulation is very great as suggested above, the planetary surface will approach a vast plain overlain by a dust-filled atmosphere.

It should be emphasized, however, that current conditions on the suface of Venus may be vastly different from conditions in the past. Urey (Ref. 3) first pointed out that H_2O is by far the most cosmically abundant oxidizing agent and that much water necessarily must have existed on Venus in the past in order to provide sufficient oxygen for CO_2. Photodissociation of H_2O, oxidation of carbonaceous molecules, and escape of hydrogen were the probable events in the depletion of Venus' water. The more rapid depletion of water from Venus than from the Earth may have been due to its closer proximity to the Sun. Urey (Ref. 3) further suggested that increasing CO_2 pressure was buffered in the presence of water by the reaction

$$CO_2 + \text{Ca, Mg silicates} \rightarrow \text{carbonates} + SiO_2$$

At room temperatures, the Gibbs free energy is negative at CO_2 pressures exceeding 10^{-5} atm. It is thus postulated that great quantities of carbonate rocks were formed on Venus until insufficient water remained on the planet as a reaction medium. At high temperatures, the reaction is reversed, and Urey supposed that the limestones were decomposed by plutonic activity to restore CO_2 to the atmosphere. Though specific events in this sequence are obviously somewhat obscure, it emphasizes the point that Venus has probably evolved through a wide spectrum of conditions.

If the illuminated side of Venus has a temperature of around 750° K and surface water pressure is negligible, surface conditions are truly in the metamorphic realm. Surface phase assemblages formed in the past may have been transformed to new assemblages which are stable under the existing environment. In general, many hydrous phases would have either partly dehydrated or have converted to new anhydrous phases at 750° K, zero water pressure, and 50 atm of total pressure. For instance, prominent hydrates on Earth such as brucite, kaolinite, chrysotile, gibbsite and goethite may not occur on the illuminated surface of Venus. There is little probability, however, of Sagan's (Ref. 22) suggestion that pools of molten lead and other metals cover much of the bright side.

Major Planetological Problems of Venus. From the foregoing section, it is fairly obvious that we must acquire some very fundamental facts about Venus before we can proceed with a complicated scientific investigation. The initial step is to develop a model for Venus as it is today. We first need to determine the surface temperature and its variations with time and location, the atmospheric pressure and atmospheric composition at the surface, the rotational period of the planet and its axial orientation, wind conditions on the planet, and, of most importance, the amount of relief on the Venusian surface. These facts would allow us to understand the surface as it is today and the modifications that it undergoes under the existing environment.

Furthermore, gross body parameters of Venus must be measured so that the present configuration and internal structure of the planet can be understood. Measurements of mass, radii, and moments of inertia are needed. Internal layering and elastic wave velocities should be obtained by seismological observations. Measurements of the surface heat flux are necessary for evaluation of the existing internal thermal regime of Venus. The strength of the magnetic field of Venus, together with knowledge of the size of the planet's core, may further the understanding of the origin of the Earth's magnetic field.

The chief problem on Venus, however, is the change that has occurred on the surface during the history of the planet. This history is probably well recorded in the stratigraphy of the surface layers of Venus, and examination of stratified rocks on the Venus surface should take major emphasis. From detailed visual, textural, and mineralogical studies of these rocks combined with relative and absolute age determinations, the geological history of the planet will be able to be reconstructed. It may be possible to ascertain when oceans existed on the planet, the time at which existing conditions started, the degree of internal melting, erosive mechanisms of the past, and the existence of past life. These investigations must consider the probable transformations that the rocks have undergone in the existing surface temperature-pressure environment and tectonic activity. Visual reconnaissance on a large scale is necessary to show the existence of fold belts which will suggest the planet's past thermal regime. The delineation of the geological history of Venus is especially important when it is considered that the evolutionary course of Venus and the Earth might be somewhat parallel because of similar mass and bulk composition, but that the rate of change on Earth has been slower because of our greater distance from the Sun.

Mars

Present State of Knowledge. Speculations concerning the bulk composition and internal structure of Mars are tied to the best values of the mass, radii, dynamic ellipticity (C-A)/C, or the ellipticity of the gravitational equipotential surface of a rotating body and optical ellipticity (actual ellipticity of the solid body regardless of the internal density distribution). Table 18–I summarizes the values from different sources for these important quantities.

TABLE 19–I.—Physical Data for the Body of Mars

Ratio of Mars' mass to Earth's mass	
0.1069	Ref. 26
0.1080±0.0002	Ref. 36
0.10766±0.00010	Ref. 34
Bulk density	
4.24	Ref. 36
3.95	Ref. 37, Ref. 38
4.04	This paper, using mass from Ref. 34, radii from de Vaucouleurs
Radii (based on astronomical unit equal to 149, 598, 845 ±250 km)	
Equatorial radius	
3329 ±6 km	Ref. 35, motion of surface markings
3400	Ref. 39, yellow light.
3374	De Vaucouleurs personal communication, 1962
Polar radius	
3291 ±17 km	Ref. 35, motion of surface markings
3355	Ref. 39, yellow light
3347	De Vaucouleurs, personal communication, 1962
Mean radius	
3310	Ref. 35
3360	De Vaucouleurs, personal communication, 1962
Ellipticity of the solid surface	
0.0108	Ref. 35
0.013	Ref. 39
0.010	De Vaucouleurs, personal communication, 1962
Dynamic ellipticity, (C–A)/C	
0.00522	Ref. 38
0.0052	Ref. 40

Measurements of the orbital characteristics of the two satellites, Phobos and Deimos, provide a value for the mass which is more accurate than the value for the mass derived from perturbations of the orbits of minor planets. Clemence (Ref. 34) finds the ratio of the mass of Mars to that of the Earth-Moon system as 0.10636 ±0.0001 and the ratio of Mars to that of the Earth alone as 0.10766 ±0.00010.

Trumpler (Ref. 35) measured the radii in light of different visible wavelengths and con-

firmed Wright's (1925) result that the diameter appeared to be smaller in the red and infrared than in shorter wavelengths because of the effects of the Martian atmosphere. The most rapid change in apparent radius occurred with wavelengths between yellow and infrared. Trumpler gave a value of 3329 $\pm$ 6 km for the equatorial radius and 3291 $\pm$17 km for the polar radius. The mean of the polar and equatorial radii was 3310 $\pm$12 km. This value is lower than those found by other investigators. De Vaucouleurs (1962, personal communication) regards the best values as 3374 and 3347 km for the equatorial and polar radii and 3360 km for the mean radius. These values from de Vaucouleurs are consistent with a polar flattening of 0.010.

Runcorn (personal communication, 1962) suggested that second-order convection might produce such an excess flattening. He has interpreted the excess flattening of both the the Earth and Moon as arising from inequalities in density caused by thermal convection currents in the bodies of the planets. Runcorn calculated that a temperature difference on the order of 300° C should exist between rising and descending currents on Mars. Surface heat-flux measurements will be able to determine if any effect of this kind is present. Recent heat-flux measurements for the Earth have delineated anomalies which commonly are interpreted as being caused by convection in the mantle. Runcorn has calculated that the temperature differences on Earth between rising and descending currents should be on the order of 1 deg.

Woollard's (Ref. 44) data on the satellite orbits also provide a value of (C-A)/Ma^2 as well as a value for C, the moment of inertia about the polar axis, if hydrostatic equilibrium is assumed (Ref. 40). Many speculative models for internal structure are possible, and MacDonald (Ref. 40) has completed several by varying assumed values for surface density and core radius sympathetically for given values of the flattening to provide a close fit of the mass and moment of inertia data. Hydrostatic equilibrium and the absence of phase transitions are assumed. MacDonald concludes on the basis of the calculations that Mars is quite likely a nearly homogeneous body, and that the "surface density" is 3.8 to 4.0 g/cc if the mean radius is as small as Trumpler's values indicate—less than 3315 km. If the mean radius is as high as 3345 km and the "surface density" is high, an iron core could be present. Several other models for the interior of Mars exist but suffer from the same inadequacies in the data as do MacDonald's. Those by Jeffreys and Bullen are discussed by de Vaucouleurs (Ref. 41).

Trumpler (Ref. 35) gave 0.0108=1/93 for the flattening of the solid rotating surface of Mars from his own measurements. He averaged direct measurements of the diameters and measurements of movements of surface markings to arrive at the result. De Vaucouleurs (Ref. 41) averaged results by many workers to get 0.013=1/77. This optical (actual ellipticity is twice as great as the dynamic ellipticity which is determined from perturbations in the orbits of the satellites. Woollard (Ref. 42) studied the motion of Deimos, and Brouwer and Clemence (Ref. 34) gave 0.005209=1/192.0 for the dynamic ellipticity from Woollard's data.

Both the Earth and the Moon also have actual ellipticities of the solid surface which are greater than their dynamic ellipticities. The bulge of the Moon toward and away from the Earth is a somewhat different problem because the Moon is not in free rotation and some doubt exists concerning even the existence of the bulge. The Moon's equatorial ellipticity is much larger than would be expected if it were a rotating fluid (Ref. 43). The excess flattening of the Earth has been interpreted as a relic ellipticity from a time when it rotated more rapidly (Ref. 44). This interpretation involves slowing of rotation by tidal friction and a finite strength for the body of the Earth. Most interpretations concerning the equatorial flattening of the Moon require considerable long-term strength for the body.

The excess ellipticity of Mars has been interpreted by Lamar (Ref. 45) as a consistent increase in the thickness of a Martian crust from the poles to the equator with a phase change defining the base of the crust. This is an artificial hypothesis requiring further explanation

for the symmetrical crustal thinning toward the poles.

The large number of variables and the probable presence of silicate phase transitions makes any specific simplified model meaningless. All that has been shown is that we must have accurate values for the figure of Mars and seismic indication of internal structure before definite conclusions can be reached.

The ratio of the dynamic flattening E to the ratio ϕ of the gravitational and centrifugal forces at the equator (Clairaut's constant) can be used as an indicator of internal inhomogeneity. A planet of uniform density gives $E/\phi = 1.25$. The ratio for the Earth, which has a metallic core equal to 55 percent of its radius and probably one or more phase transitions in the mantle, is 0.974. Depending upon values taken for the radii, the ratio for Mars is 1.13 to 1.21, indicating some vertical density increase slightly above that which would be expected from simple compression. Urey (Ref. 46) has calculated 1.22 for the compressed Clairaut's constant without phase transitions. The presence of a phase transition (e.g., olivine structure→spinel structure or orthopyroxene→corundum structure) is independent of chemical differentiation of a planet and possibly accounts for the entire observed depression of the Clairaut's constant.

The average bulk density again depends upon values for the radii. Recent computations vary with a range of 0.3 g/cc and are given in Table 18–I. These lead to a value for uncompressed density of about 3.7 to 3.9, assuming a silicate phase transition. Central pressure in Mars is well in excess of the 1 to 1.5 x 10^5 bars needed to produce major phase transitions at Earth temperature gradients. Such a bulk density corresponds to a peridotite body with 10 to 15 percent free metallic phases. In comparison, the core of the Earth is 31.5 percent of its mass, while the Moon may have only a negligible amount of free metal.

If Mars and/or the Moon have differentiated sufficiently to form a crust, comparison of crustal rocks and crustal dimensions with the Earth will be of great interest. At present, we know neither the near-surface rock types nor the depth of a hypothetical crust for either Mars or the Moon.

MacDonald (Ref. 40) computed some simplified thermal models for Mars. He concluded that if the radioactivity is equivalent to that of chondritic meteorites, the melting point of iron should be reached at some shallow depth, the specific depth depending upon the distribution of the radioactive elements. The implication is that the liquid iron should have formed a core equal to 10 to 15 per cent of the mass of the planet. A core of that size is too large to fit his preferred model of density distribution, assuming Trumpler's value for the radius. MacDonald concluded, therefore, that Mars does not have a radioactive content equal to chondritic meteorites.

It is evident just on the basis of comparative bulk densities that Mars, the Earth, the Moon, and Mercury all have different bulk compositions. Adequate thermal models have not been calculated for any one of the bodies, basically because we know the Earth is too complicated for a simple model and Mars and the Moon do not fit the original "average chondrite" assumption. Experiments aimed directly at delineating the differences in bulk composition, internal structure, and present thermal state will be of most scientific value.

Experiments of primary importance with regard to the internal structure of Mars are to obtain accurate values of the radii and seismic evidence.

Topographic features on Mars can be inferred from irregularities in the distribution and breakup of the polar ice caps and the color tone variations which move across the surface in the dark areas. Plateaus and valleys must be present, but these and other features are assumed to have relief less than 6000 to 7000 ft because they cast no shadows that are visible from Earth. A localized remnant of the winter south polar cap persists into the spring; the area is inferred to be a plateau about 3000 ft high on the basis of vertical atmospheric temperature calculations. Localizations of the spreading of dark fringes from the polar caps toward the equator during spring are persistent through the years and are interpreted as water-bearing valleys. The *canals* on the surface also become darker in the spring and are inferred to be valleys carrying either groundwater or thin surface condensations of water from the evapo-

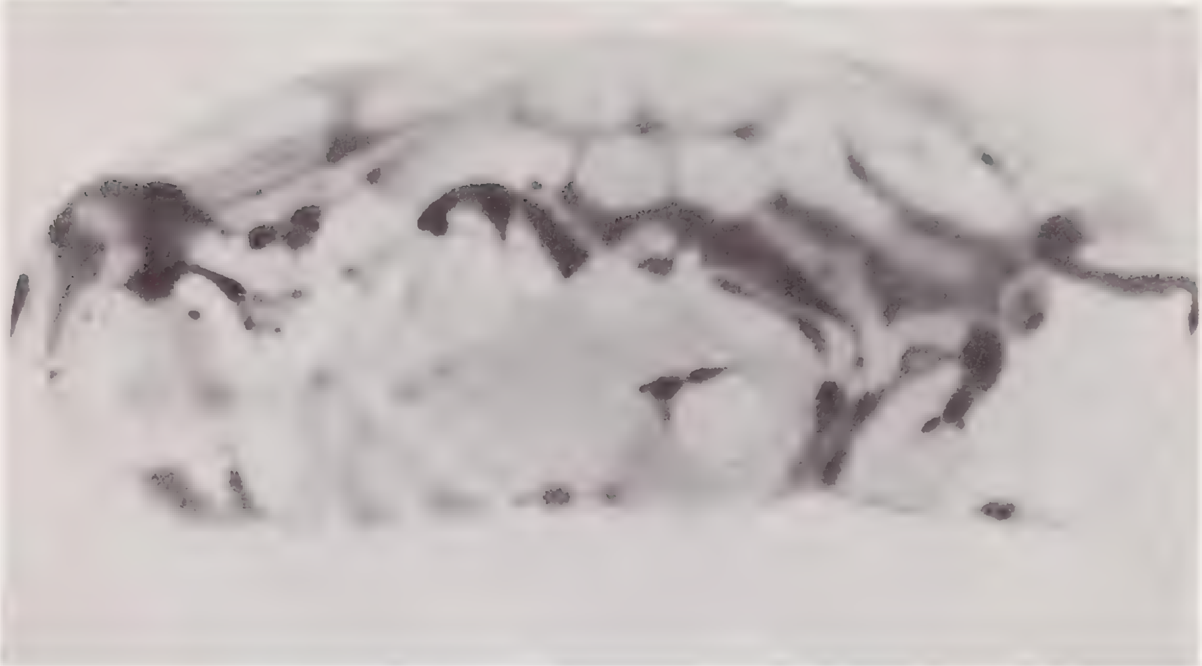

FIGURE 18-12.—Map of Mars based on observations by Dr. G. de Vaucouleurs with the 24-inch refractor of Lowell Observatory, Flagstaff, Arizona, in October and November 1958. (Aitoff equal area projection—Central Meridian 180°—South at top. Season: end of Winter of Northern Hemisphere. Courtesy of G. deVaucouleurs.)

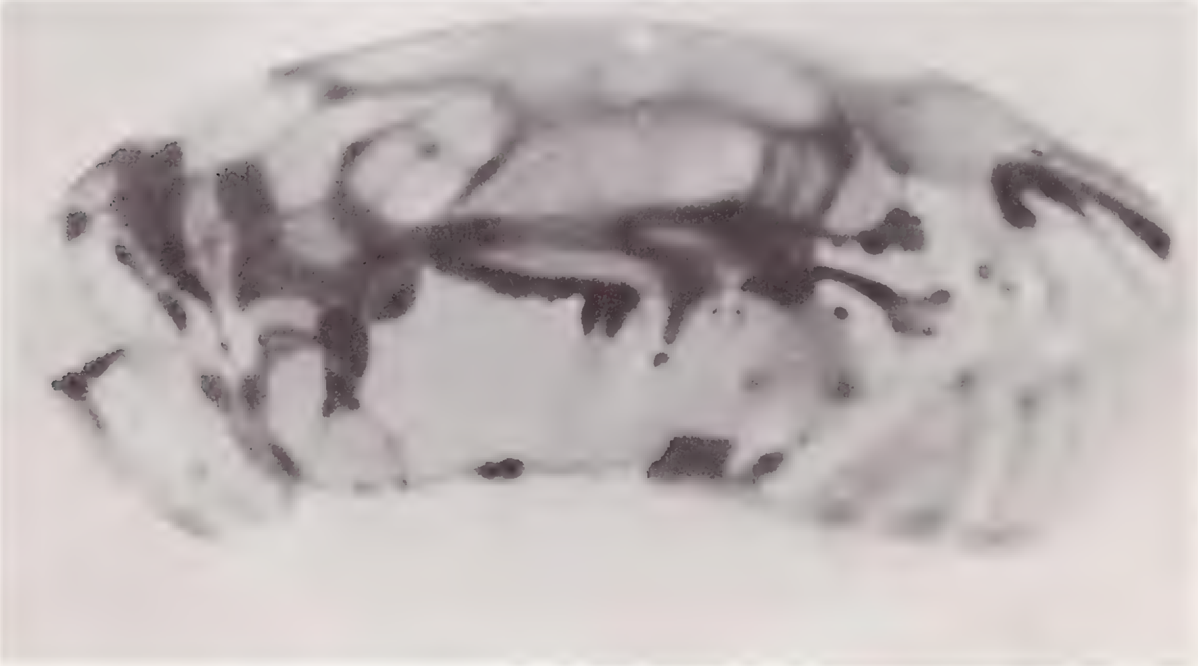

FIGURE 18-13.—Map of Mars based on observations by Dr. G. de Vaucouleurs with the 24-inch refractor of Lowell Observatory, Flagstaff, Arizona, in October and November 1958. (Aitoff equal area projection—Central Meridian 0°,—South at top. Season: end of Winter of Northern Hemisphere. Courtesy of G. deVaucouleurs.)

rating polar caps. The water should not be liquid at the temperatures and pressure prevailing, and description of the actual mode of transport of water is a problem.

Horizontal telescopic resolution with photography is about 150 km at the closest oppositions. Visual telescopic resolution is about 80 km. Sharp surface topography such as stratovolcanoes, mountain chains, steep valleys, large impact craters, etc., should be visible and probably do not exist to the extent that such features are present on the Earth or Moon. However, negative topographic features such as impact craters or graben may have become filled with dust from the frequent dust storms of planetary dimensions. The *canals* may be lowlands which could be analogous to large graben or trenches on Earth. The existence of large-scale topography which might be analogous to ocean basins and continents on Earth, or maria and highlands on the Moon, is as yet unproven. Photographic data on the Martian topography should be the primary aim of our first experiments.

About three-fourths of the surface of Mars is covered by so-called "bright areas," which are orange-colored and have been interpreted as deserts. The composition of these is inferred from polarization studies and IR reflectivity. De Vaucouleurs points out that siliceous volcanic rocks fit the IR studies well, and powdered "limonite" (hydrated iron oxides) fits the polarization curve quite well. It is possible that the bright areas are composed of slicates because of the strong absorption in the thermal flux in the 8 to 10 μ region, and that considerable oxidized iron exists, perhaps as grain coatings, perhaps as a desert-varnish type of encrustation.

The remaining one-fourth of the surface is "dark area." These areas have generally well-known configurations, but their color tones change seasonally. The changes have been interpreted as moving fronts of vegetation, groundwater, or both. Parts of dark areas which are covered by dust storms have some regenerative power and reappear in a matter of weeks or months.

Figures 18–12 and 18–13 are maps drawn by de Vaucouleurs of Mars showing the typical distribution of features and shadings. Figure

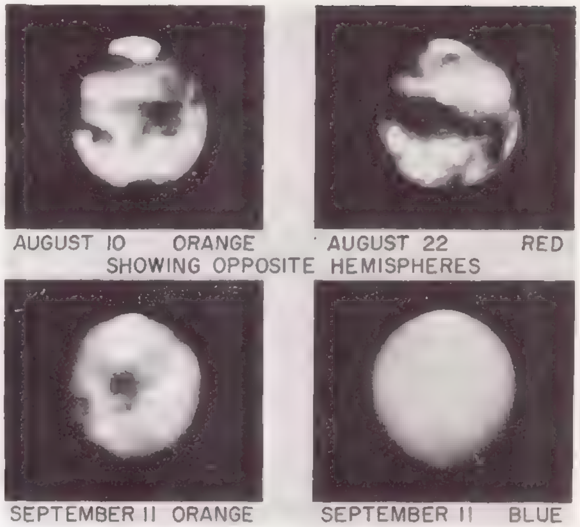

FIGURE 18–14.—Photographs of Mars in different colored light, in different months, during the opposition of 1956. (Wilson and Palomar Observatories photographs.)

18–14 shows photographic images of Mars in red, orange, and blue light in different months. The atmospheric haze in September has obscured much of the detail visible in August. Little but the polar cap shows in blue light. This "blue haze" is not fully understood.

The Martian climatic variation is analogous to that of high deserts on the Earth. Surface temperature variations are approximately from 200 to 300° K. Diurnal variations may be about 80° K. Wind and dust storms are common. Because atmospheric pressure is about 80 mb and the mean temperature for the entire illuminated disk is about −40° C, liquid water must exist only rarely on the surface, if at all. The polar caps must sublime rather than melt. (Ref. 41).

Mercury

Mercury never rises more than 28 deg above our horizon because of its proximity to the Sun. Observations of Mercury from Earth, therefore, have been hindered by the great thickness of the Earth's atmosphere at this declination. Visual and photographic observations, however, are sufficient to show definite broad surface features of contrasting brightness on Mercury. These features generally resemble lunar maria and continents. Figure 18–15 is a series of drawings of Mercury made from visual obser-

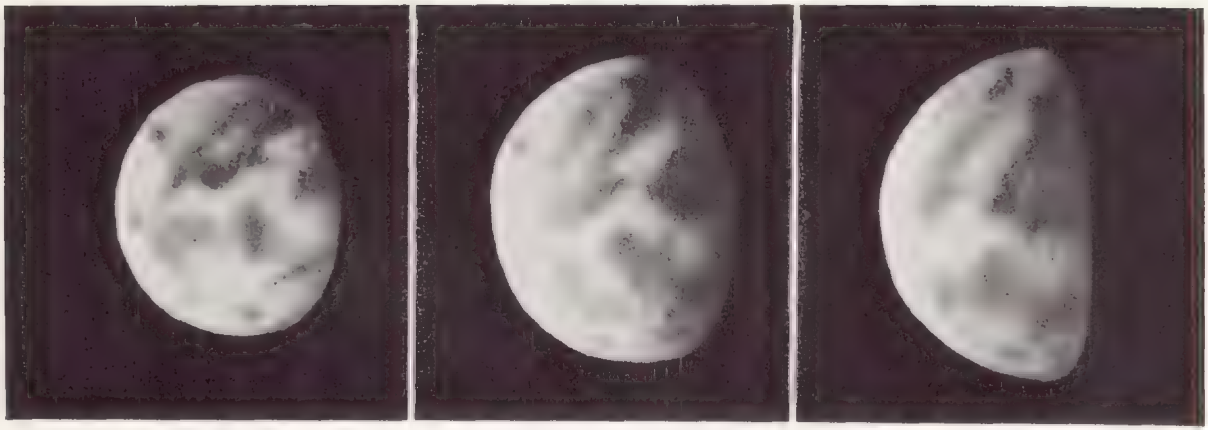

FIGURE 18-15.—Drawings of Mercury. (Observations with a 60-cm refractor on October 6, 12, and 19, 1950. Each drawing based on 3–6 observations made by Dollfus on neighboring dates (Dollfus, 1953).)

vations of the planet in 1950 (Ref. 49). The resolution in these drawings is about 300 km for two points of considerable contrast. Figure 18–16 is a planisphere of Mercury (Ref. 49) which summarizes ten composite photographs.

The photometric and polarimetric properties and the albedo of Mercury are similar to those of the Moon. Shadow studies indicate that the relief on Mercury is about the same as on the Moon.

Mercury's rotation period is synchronous with its orbital period so that one side of Mercury is eternally illuminated. Because of a large libration in longitude, only 30 percent of the planet's surface is in darkness. No atmosphere has been detected on Mercury. The temperature at the subsolar point is about 685°K, whereas the back side should be exceedingly cold. If an atmosphere ever existed on Mercury, most constituents should have condensed in the cold trap on Mercury's dark side.

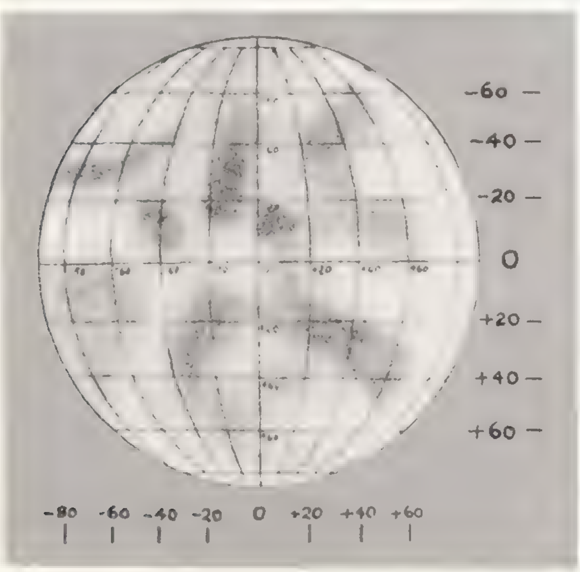

FIGURE 18-16.—Planisphere of Mercury by A. Dollfus summarizing the spots observed on 10 composite photographs obtained in 1942 and 1944 (Dollfus, 1953).

Body measurements of Mercury are most uncertain. Measurements of the diameter are varied, and resolution is insufficient to determine the oblateness of the body. In theory, a large tidal bulge toward the Sun should exist. Estimates of the mean density of Mercury range from 3.8 to 6.1. These densities indicate, however, that Mercury must have a different bulk composition from the Moon, a body of similar apparent volume but much lower density. Assuming Mercury to be composed of silicates and a metal phase, the percent metal phase corresponding with the range of mean densities is 24 to 84. The apparent high density of Mercury has been a strong factor in theories of condensation and accumulation processes during formation of the solar system.

SOME CURRENT NEEDS IN PLANETOLOGY RESEARCH

It is apparent from this brief review of our understanding of the Moon and terrestrial planets that many lines of Earth-based research will improve our meager knowledge of these bodies. No attempt has been made, however,

to summarize current research efforts and planned spacecraft experiments; rather, several lines of Earth-based research will be suggested which could be scientifically profitable.

1. Color photography of the Moon and a quantitative study of the color contrasts on the Moon using new films sensitive to a narrow band of wavelengths.

2. Spectrophotometric mapping of the Moon.

3. Laboratory investigations of petrological reactions under vacuum conditions and under the physical conditions found on the terrestrial planets.

4. Acoustic velocity measurements combined with petrological examinations of the samples being measured.

5. A study of the effects that X-rays, solar corpuscular radiation, cosmic ray bombardment, and ultraviolet radiation have on common silicate minerals.

6. Investigations into the possibility and techniques of extracting the life-supporting elements, hydrogen, oxygen, phosphorus, etc., from common igneous rocks.

7. A study of the ability to recognize and distinguish major structural and geologic features from photographs of poor resolution.

8. Further theoretical investigations into predicting the amount of seismicity on the Moon and terrestrial planets, with particular emphasis on the ability to predict and agree with the observed seismicity for the Earth.

9. Investigations into the origin and nature of magnetic fields in the terrestrial planets.

10. Development of remote methods of textural, mineralogical, chemical and isotopic analysis, including analysis for different oxidation states of iron, titanium, and manganese.

11. Study of methods for measurement of surface features through thick planetary atmospheres (e.g., use of far-infrared photometry or photography).

12. Studies of polarization from terrestrial surfaces for purposes of correlation with lunar and planetary data.

13. Measurements of physical properties (thermal and electrical conductivity, specific heat, etc.) of granulated silicates as a function of temperature, atmospheric pressure, packing and grain size.

14. Theoretical, experimental, and model studies on mechanics of high-velocity impact.

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